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AN EXPERIMENTAL STUDY OF TRANSONIC BUFFET OF A SUPERCRITICAL AIRFOIL WITH TRAILING EDGE FLAP

by

B.H.K. Lee and F.C. Tang

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AN EXPERIMENTAL STUDY OF TRANSONIC BUFFET OF A SUPERCRITICAL AIRFOIL WITH TRAILING EDGE FLAP

ÉTUDE EXPÉRIMENTALE DU BUFFET TRANSSONIQUE D'UN PROFIL AÉRODYNAMIQUE SUPERCRITIQUE MUNI DE VOLETS DE BORD DE FUITE

by/par

B.H.K. Lee and F.C. Tang

National Aeronautical Establishment

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SUMMARY

A supercritical airfoil with a trailing edge flap has been the subject of aerodynamic investigation in the National Aeronautical Establishment's High Reynolds Number 2-D Test Facility. The effects of flap deflection on buffet intensities and delay of buffet onset at transonic speeds were studied. Buffet boundaries for various flap angles were determined from the divergence of the fluctuating balance normal force measurements (C_N'). The onset of buffet was obtained from plots of C_N' versus C_L at values of C_L where the slope was 0.1. This value for the slope was arbitrarily chosen, but was found to give consistent results which agreed well with values computed from the criterion using the trailing edge pressure divergence for those cases where buffet onset is primarily due to trailing edge separation.

For given flow conditions the deflection of the trailing edge flap altered the circulation and hence the position of the shock wave and its strength. The variations of these two quantities with flap angles were determined from pressure measurements carried out on the airfoil surface. The test was performed quite deep inside the buffet régime and shock wave oscillations were investigated from spectral analyses of the balance outputs. Fluctuations in the shock motion of approximately 70 Hz were detected.

The drag of the airfoil was computed from the wake stagnation pressure deficit and the drag penalties for large flap angles were quite significant. Analysis of the wake profiles with flap settings was carried out to study the changes in wake characteristics.

This investigation shows that trailing edge flap is a useful device for passive buffet alleviation of supercritical airfoils. For Mach numbers less than the design values, the lift coefficients at buffet onset are very close to and in some cases correspond to $C_{L_{max}}$. This is quite unlike conventional airfoils when regions of mild, moderate and heavy buffet can be detected before $C_{L_{max}}$ is reached.

RÉSUMÉ

Un profil aérodynamique supercritique muni de volets de bord de fuite a fait l'objet d'une étude aérodynamique à l'installation d'essais bidimensionnels avec nombre de Reynolds élevé de l'Établissement national aéronautique. Les effets de la sortie des volets sur l'intensité du buffet et le retard de ces vibrations aux vitesses transsoniques ont été étudiés. Les limites du buffet pour différents angles des volets ont été déterminées à partir de la divergence des fluctuations de la force normale de la balance (C'_N). L'apparition du buffet a été déterminée à partir des courbes de C'_N en fonction de C_L aux valeurs de C_L où la pente est égale à 0,1. Cette valeur de la pente a été choisie arbitrairement, mais s'est avérée la valeur qui donne des résultats qui sont systématiquement conformes aux calculs découlant du critère basé sur la divergence de pression au bord de fuite, lorsque les vibrations tiennent principalement à la séparation du bord de fuite.

Dans des conditions d'écoulement données, la sortie des volets du bord de fuite ont modifié la circulation et, partant, la position et l'amplitude de l'onde de choc. Les variations de ces deux paramètres en fonction de l'angle des volets ont été déterminées à partir de mesures de pression effectuées sur la surface du profil. L'essai a été mené en plein régime des vibrations, et les oscillations de l'onde de choc ont été étudiées à partir d'analyses spectrales de la réponse d'équilibre. Des fluctuations d'environ 70 Hz ont été décelées dans le mouvement de choc.

La traînée du profil a été c alculée à partir de la dépression dans la zone de stagnation du sillage, et une pénalité importante de la traînée est notée aux grands angles de sortie des volets. L'analyse des profils du sillage en fonction de différents réglages des volets visait à étudier les changements dans les caractéristiques du sillage.

Cette recherche montre que les volets du bord de fuite est un dispositif utile pour atténuer passivement l'intensité du buffet des profils supercritiques. Pour les nombres de Mach inférieurs à la valeur du calcul, les coefficients de portance à l'apparition du buffet approchent et égalent parfois $C_{L_{max}}$. Ces profils diffèrent beaucoup des profils classsiques pour lesquels on peut déceler le buffet faible, moyen et intense avant que C_L ne soit maximal.

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List of Symbols

b	model span
c	chord length
C_D	drag coefficient from wake integration
C_L	lift coefficient from balance measurement
C_{L_P}	lift coefficient from pressure integration
$C_{L_{max}}$	maximum lift coefficient from balance measurement
C_N	normal force coefficient from balance measurement
C'_N	rms value of fluctuating normal force coefficient defined in Eq. 1
C'_{N_B}	rms value of fluctuating normal force coefficent at buffet onset
C_P	pressure coefficient
C^*_P	pressure coefficient at M = 1
ΔC_{P_S}	shock strength
$C_{P_{TE}}$	pressure coefficient at trailing edge
$\Delta C_{P_{TE}}$	defined in Eq. (2)
$C_{P_{TEdiv}}$	divergence trailing edge pressure coefficient
M	Mach number
M_D	drag rise Mach number
M_{DES}	design Mach number
N_{rms}	rms value of normal force from balance measurement

List of Symbols

q_∞	free stream dynamic pressure
R_c	Reynolds number based on chord length
t	maximum thickness of airfoil
w	thickness of wake
x	distance measured in the flow direction from the airfoil leading edge
x_s	shock position
y	distance traversed by wake probe, perpendicular to flow direction
α	angle of incidence
α_{div}	angle of incidence when trailing edge pressure divergence occurs
$\Delta\alpha$	defined in Eq. (3)
δ	flap angle

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1.0 Introduction

Buffeting is the dynamic response of an aircraft as a result of aerodynamic excitation arising from random loading on the wing when the flow separates. For supercritical airfoils, flow separation can occur at the shock wave or at the trailing edge. The separated flow region behind the shock usually starts out as a bubble and grows downstream as buffet becomes more severe until the flow is completely separated. On the other hand, trailing edge separation moves upstream until it reaches the shock wave. There are instances when both types of separation occur simultaneously and the two separated regions merge (Reference 1).

A number of studies (Refs. 2, 3, 4) on buffet characteristics have appeared in recent years and prediction methods of buffet intensities are also available (Refs. 5-10). For the aircraft designer the buffet onset boundary provides important information to enable him to specify the cruise condition of the aircraft. For buffet associated with trailing edge separation a theoretical prediction method has been proposed (Refs. 10, 11). However, for shock induced separation, the method is not applicable and usually wind tunnel tests are necessary to define the buffet onset boundary. Trailing edge pressure divergence is usually not a reliable indication of buffet onset in such circumstances since the pressure will not be affected until the separation bubble reaches the trailing edge. At the National Aeronautical Establishment (NAE), buffet onset is identified from the divergence of the normal force obtained from a balance output. This has been found to give reliable results for buffet onset associated with both types of flow separation.

Investigations into methods for buffet alleviation for supercritical airfoils are virtually non-existent. Some earlier studies of conventional airfoils with flaps (Refs. 12, 13) show that buffet boundaries can be raised appreciably by increasing the flap settings. Trailing edge flaps are found to be more effective than leading edge flaps for providing large lift increments and as a means for buffet control. In order to gain more insight into the effects of flaps on buffet intensities and delay of buffet onset at transonic conditions, a

wind tunnel investigation of a supercritical airfoil with a trailing flap was carried out. An understanding of the effects of a flap on the characteristics of the separated flows is useful in assessing the deployment of trailing edge flap as a passive means for buffet alleviation.

This report gives a brief description of the experimental arrangements and the procedure for data processing. The main emphasis in the report is in the presentation of data which shows the effects of flap angles on buffet characteristics of this airfoil. The conclusions derived from these results are in general believed to be applicable to other supercritical airfoils.

2.0 Facility, Model and Instrumentation

The investigation was carried out in the NAE Two-Dimensional Test Facility (Ref. 14) using an airfoil designed by the de Havilland Aircraft of Canada. The airfoil was used in a previous joint NAE-de Havilland research and development program aimed at improvements in design that would reduce wing section drag.

The airfoil (Figure 1) studied was basically the same model used in the investigation reported in Reference 15, but with the addition of a trailing edge flap. It was made of aluminum having a chord of 12 inches and a span of 15 inches. The maximum thickness to chord ratio was 16%. The flap was approximately 14% chord and the trailing edge thickness was 0.1% chord. There were 80 pressure ports on the airfoil and flap surfaces, for static pressure measurements, including one at the trailing edge. The drag of the airfoil was obtained from wake measurements using a traversing rake with probes at four spanwise locations located approximately 18 inches from the airfoil trailing edge. In this experiment, only the two centrally located probes were used and their average was taken for drag measurements. The design conditions for this airfoil were for a cruise Mach number of 0.72 and lift coefficient of 0.6.

The lift and pitching moments were determined from a side wall balance. In addition to the steady state values of the balance outputs, the fluctuating quantities were also measured. In this report

only the rms value of the normal force results are presented and this quantity is denoted by:

$$C'_N = \frac{N_{rms}}{q_\infty bc} \qquad (1)$$

where N_{rms} is the rms value of the balance normal force output, q_∞ the free stream dynamic pressure, b and c the span and chord of the model respectively. Spectral analyses of the balance output were also performed. The signal was sampled at 1.6 KHz and analyzed on a VAX 11/785 computer using the IEEE package PMPSE (Ref. 16) to give power spectra and auto-correlation functions. A transform size of 256 and a signal duration of 2 seconds were chosen in the analyses.

Distributed suction was applied through porous plates to regions of the tunnel side walls in the vicinity of the model. The amount of suction was selected so as to minimize any three-dimensional effects.

All the tests were performed at a chord Reynolds number of approximately 20 million. The Mach number varied between 0.612 to 0.792 and the flap angle settings were δ = 0°, 4°, 8°, 14°, -4° and -8°. The standard convention of positive flap deflection in the downward direction was adopted.

3.0 Results and Discussions

Representative results from this experimental investigation are discussed in this report. A full account of the experimental data can be found in Reference 17.

3.1 Lift and Normal Force Fluctuation from Balance Measurements

For supercritical airfoils it is often noted from the C_L versus α curves that up to moderate angles of incidence and Mach numbers greater than the drag rise value M_D ($\frac{dC_D}{dM} = 0.1$) at design condition, C_L does not usually reach a maximum. However, below M_D, a

value of $C_{L_{max}}$ is detected and this is illustrated in Figure 2 for a flap deflection angle δ of zero degree. The behavour is similar for all the flap settings carried out in this test.

The effect of flap angles on the lift coefficient is shown in Figure 3 for a Mach number very close to the design value of 0.72. The increase in lift for positive flap angles is quite significant. Mach number effects are shown in Figures 4 and 5 at two Mach numbers below and above the design value. The buffet onset conditions are also marked on Figures 3 to 5, and it can be seen that the C_L at the onset of buffet is very close to and in some cases corresponds to $C_{L_{max}}$ for M less than M_D.

The effect of changing flap angles on the fluctuating normal force is illustrated in Figures 6 to 8 for values of the Mach number similar to those given in Figures 3 to 5. Near M_{DES}, Figure 6 shows an increase in C_L before buffet sets in for positive increments of the flap angle, while negative flap settings will give a smaller value of C_L at buffet onset. At M about 0.673 (Figure 7), all the curves show a maximum C_N' . For C_L below the buffet onset value, the magnitudes of C_N' for non zero flap angles show some increase above the level for $\delta = 0°$. On increasing Mach number to about 0.772 (Figure 8) it is seen that the curves of C_N' versus C_L do not have negative slopes and the magnitudes of the normal force fluctuations are considerably lower than those given in Figures 6 and 7.

3.2 Buffet Boundaries

To determine the C_L at buffet onset, the rms values of the normal force fluctuations C_N' are plotted versus C_L as shown in Figure 9 for $\delta = 0°$. The procedure is to obtain a smooth C_N' versus C_L curve either by spline fitting or manually. C_L at buffet is obtained by noting the point on the curve with a slope $dC_N'/dC_L = 0.1$. This value is arbitrarily chosen, but in those cases where buffet onset is primarily due to trailing edge separation, this criterion for deriving the buffet boundary is found to give consistent results and agrees with values computed from trailing edge pressure divergence. It is

interesting to note from this figure that some of the curves show that C_N' reaches a maximum and then decreases. For M = 0.772 and 0.792, a very rapid increase in C_N' is not detected and the slopes of the curves do not become negative since there is no $C_{L_{max}}$, as illustrated in Figure 2.

The buffet boundaries for various flap settings are shown in Figures 10 and 11. Figure 10 shows C_L plotted against M and it is seen that the boundaries can be raised appreciably and there is a large increment in lift with positive changes in δ. Characteristic of supercritical airfoils, the buffet boundary decreases rapidly for $M > M_{DES}$. At M = 0.75 which corresponds to the drag rise Mach number M_D at design C_L, this airfoil shows only small improvements in alleviating buffet by the use of flaps. Further increase in Mach number again show an increase in the lift before encountering buffet. Figure 11 gives the buffet boundaries plotted as α versus Mach number. The angle of incidence at which buffet occurs is obtained from the C_L versus α curves using the buffet onset value of C_L given in Figure 10. For $M > M_{DES}$, it is difficult to determine α accurately since C_L at buffet is very close to and in some cases correspond to $C_{L_{max}}$, and small errors in C_L magnifies considerably in terms of α.

For conventional airfoils, it is often possible to designate regions of mild, moderate or heavy buffeting. Because buffet onset occurs so close to $C_{L_{max}}$ for M near or less than M_{DES}, it is not too meaningful to assign a degree of severity except when M is greater than some value, for example, M_D for this particular airfoil. Figures 12-17 show the buffet onset boundaries and curves with given buffet intensities for various flap angles. Also shown in the figures are the values of $C_{L_{max}}$ for those values of M where a maximum in C_L can be detected.

3.3 Pressure Distributions on Airfoil Surface

Static pressure measurements were obtained from 50 and 30 pressure ports on the upper and lower surface of the model respectively. The C_p distributions for the airfoil near the design Mach

Number for zero flap setting are shown in Figure 18 for various angles of attack. According to Figure 11, at the Mach number of interest (0.722), buffet occurs at $\alpha = 3.4°$. It can be seen that the shock waves for the larger α are not as sharply defined as those for $\alpha < 3.4°$.

The effects of varying δ are shown in Figures 19-22 for four Mach numbers. At Mach number close to M_{DES}, Figure 19 shows the pressure distributions at α about 4.5°. It was difficult in the tests to keep both α and M constant. The values of α for $\delta \geq 0°$ are well into buffet régime (pronounced TE separation) while that for $\delta = -4°$ is slightly greater than the buffet onset value. For $\delta = -8°$, α is just below the buffet boundary.

Figure 20 shows the C_p distributions at M about 0.612 for α about 6.5°. Except for the $\delta = -8°$ curve, all the other curves are for α values larger than the buffet onset value. The pressure distribution behind the shock shows a shock induced separation bubble. Quite deep inside the buffet régime, Figure 21 shows that a well defined shock wave is not observed. In Figure 22 which is at a higher Mach number (M about 0.791), the shock wave becomes less unsteady even though the values of α exceeded those at buffet onset given in Figure 11 by a fair amount.

3.4 Power Spectra of Balance Normal Force

The IEEE computer program (Ref. 16) for computing power spectra was used in spectral analyses of the normal force outputs from the balance. Figure 23 shows the results using a FFT block size of 256 and a signal length of 2 seconds. The sampling frequency was 1.6 KHz. The conditions of this figure correspond to those in Figure 19. For $\delta \geq 0°$, the spectra show distinct peaks at approximately 70 Hz. Similar results were obtained in a previous investigation of the BGK No. 1 airfoil (Ref. 3) and they were identified as due to oscillations of the shock wave. Higher frequency peaks are present when the flap angle is increased. For $\delta = -4°$, the airfoil is operating slightly inside the buffet régime while for $\delta = -8°$ it is outside the buffet boundary. No distinct 70 Hz peaks are detected for these two flap

angles because the shock waves are quite steady as can be seen from the C_p distributions in Figure 19.

In Figure 24, the values of M and α are the same as those in Figure 20. Except for $\delta = -8°$, the airfoil is experiencing buffeting. The intensities of C_N' are not as large as those in the previous figure and the higher frequency peaks are also not so pronounced. Figures 25 and 26 are for the same conditions as Figures 21 and 22 and the airfoil is quite deep into the buffet régime. The poorly defined shock waves in Figure 21 indicate that they are very unsteady and are shown in Figure 25 as very large and distinct peaks of approximately 70 Hz. As the Mach Number increases, the magnitudes of C_N' decrease and Figure 22 shows the shock waves to be more steady. The spectra in Figure 26 clearly indicate the shock oscillations to be much weaker than those in the previous figure.

3.5 Shock Positions and Strengths

When the shock wave is oscillating, its location determined from the C_p plots falls within the range of positions that may occur during one pressure scan cycle of approximately 2½ seconds. When buffet is severe or C_N' is large, locating the shock position is difficult. In this report, the position and strength of the shock wave are defined in a manner similar to the definition used in Reference 18 (Figure 27). There is certain arbitrariness in this definition, but for large oscillating shock motion, this gives more easily measured and consistent results.

The effects of Mach number on shock location x_s/c is shown in Figure 28 for trailing edge flap angle $\delta = 0°$. Except for the two higher Mach numbers (M = .772, M = .792) which show x_s/c to decrease with α, it is seen from the other cases that x_s/c increases with α and reaches a maximum before decreases slowly. Figure 29 gives the shock locations for various flap angles at a Mach number of 0.723. The following two figures (Figures 30, 31) show x_s/c at Mach numbers below and above the design value. The motion of the shock wave with α is quite different for these two cases. The variation of x_s/c with Mach number is illustrated in Figure 32 for an angle of incidence $\alpha = 3°$.

The curves show the shock position to move downstream with increasing Mach number until a maximum x_s/c is reached. From then onwards it moves gradually upstream or in some instances remains more or less stationary. Similar trends are observed when the shock locations at buffet onset are plotted against Mach number for various flap angles (Fig. 33).

The shock strengths ΔC_{P_S} corresponding to the conditions in Figures 28-31 are given in Figures 34-37. They increase with α irrespective of whether the shock moves upstream or downstream. At a constant angle of incidence $\alpha = 3^\circ$ (Figure 38), ΔC_{P_S} varies slightly with Mach number for $M < 0.72$ even though the change in shock position is very large (Figure 32). For $M > 0.72$ (corresponding to its design value), changes in x_s/c and ΔC_{P_S} are small compared to their variations with Mach Number for $M < 0.72$. Figure 39 shows a plot of the shock strengths at buffet onset against Mach number for various flap angles. The shock strength decreases almost linearly with increasing Mach number up to the design value.

3.6 Trailing Edge Pressure Measurements

In this study on buffet characteristics of a supercritical airfoil, the trailing edge pressure was measured as the airfoil operating condition moved into the buffet régime. From the pressure coefficient versus α plots, the value of the trailing edge pressure $C_{P_{TE}}$ when divergence occurred (onset of buffet) was noted together with the value of α. The severity of buffet is denoted in terms of $C_{P_{TE}}$ as

$$\Delta C_{P_{TE}} = C_{P_{TE}} - C_{P_{TEdiv}} \qquad (2)$$

where the subscript 'div' denotes the value of $C_{P_{TE}}$ at divergence (Ref. 1). The intrusion into the buffet régime is expressed in terms of the angle of incidence as

$$\Delta\alpha = \alpha - \alpha_{div} \qquad (3)$$

Figure 40 shows the change in trailing edge pressure coefficient with $\Delta\alpha$ for M = 0.723. It is seen that $\Delta C_{P_{TE}}$ decreases monotonically with $\Delta\alpha$. For the range of Mach numbers tested, it is observed that for M < 0.72, $C_{P_{TE}}$ at $\delta = 8°$ and 14° shows smaller drop with $\Delta\alpha$ than for the other values of δ. For higher Mach numbers (Figure 41), the curves for the smaller values of δ do not cross each other as in low Mach numbers (Figure 42), and show quite distinctly that as δ increases, smaller decreases in trailing edge pressure will result.

To study the change of normal force fluctuations with trailing edge pressure, define

$$\Delta C'_N = C'_N - C'_{N_B} \qquad (4)$$

where C'_{N_B} denotes the value at buffet onset. The two quantities $\Delta C'_N$ and $\Delta C_{P_{TE}}$ are plotted in Figure 43 for M = 0.723. Figures 44 and 45 show the effects of Mach numbers for M = 0.673 and 0.772. Based on results for other Mach numbers tested, it can be concluded that in the neighbourhood of M_{DES}, much larger changes in $\Delta C'_N$ with $\Delta C_{P_{TE}}$ occur than at M lower or higher than M_{DES}. In the range of Mach Number near M_{DES} the effects of flaps show consistently that increasing δ results in larger $\Delta C'_N$ changes with $\Delta C_{P_{TE}}$. This range of Mach numbers is near the "elbow" of the buffet onset boundaries (Figure 10) and force measurements have shown large fluctuations because of the strong shock oscillations.

3.7 Drag Measurements

The drag polar determined from wake measurements is shown in Figure 46 for flap angle $\delta = 0°$. Included in this figure are the drag values at buffet onset. It can be seen that the drag rise from its value at design conditions ($C_D \approx 0.01$) is quite appreciable at buffet.

The effect of flap angles on C_D is demonstrated in Figures 47-49. Near the design Mach number, the drag is the lowest for the zero flap setting at the design C_L. The effects of Mach number are given in Figures 48 and 49 for M equal to 0.673 and 0.772 respectively.

Using the results from the drag polars, C_D can be plotted versus M for various C_L. Figure 50 shows results presented for $\delta = 0°$. At design conditions the drag rise Mach number, using the criterion based on a slope of $dC_D/dM = 0.1$ is determined to be 0.75.

At the design $C_L = 0.6$, C_D versus M are plotted in Figure 51 for various flap angle settings. Small flap angles ($\delta = \pm 4°$) do not increase the drag significantly, however, the 8° and 14° flaps appear to have quite a large effect. For off design conditions ($C_L = 0.4$ and 0.8), Figures 52 and 53 show the drag increase for negative flap angles is much larger than that for positive flap angles.

For a given flap setting and C_L, curves such as those given in Figures 50-53 can be used to determine the drag rise Mach number and the corresponding value of drag coefficient C_D. Curves of C_L corresponding to the evaluated M_D can be plotted as shown in Figure 54 for various flap settings. Positive flap angles help to delay the drag rise Mach number for off design conditions at values of C_L approximately greater than 0.75 for this particular airfoil.

The drag coefficient corresponding to the C_L at the drag rise Mach number is plotted in Figure 55. At the design $C_L = 0.6$, the zero flap airfoil gives the lowest drag at the drag rise Mach number of 0.75.

3.8 Wake Profiles

Some representative results for the wake profiles are given in Figures 56-58. The growth of the wake at $M = 0.723$ and $\delta = 0°$ is shown in Figure 56 for probe #2 of the traversing rake, and its location is 1.75 inches from the tunnel centre line. The distance y traversed by the wake probe is normalized with respect to the airfoil chord and C_D' on the horizontal scale is proportional to the total pressure drop. The integral of C_D' over the width of the wake gives the total drag. Beyond buffet onset, which occurs approximately at $\alpha = 3.4°$ in this case, the profiles become very unsteady and C_D' shown are values that occur in one pressure scan. The duration of a scan depends on the width of the wake and the traversing speed, but will not exceed a maximum value of $2\frac{1}{2}$ seconds.

The changes in wake profiles at M = 0.723 with δ for two values of the incidence α are shown in Figures 57 and 58. At α about 2.75°, the airfoil is slightly inside the buffet régime for δ = 4° and moderately deep into buffet at δ = 14° while for $\delta \leq 0°$, the airfoil is not experiencing buffet. At α in the neighbourhood of 4.5° the airfoil is buffeting except for δ = -8° which is very close to the onset boundary.

As an indication of the growth of the wake, its width w is measured and normalized with respect to the airfoil maximum thickness t. The value of w is determined from the wake profile at a value of C_D' equal to one percent of its maximum. Figure 59 shows the effect of Mach number at zero flap deflection. The buffet onset value of α is also included in the figure for reference. It is seen that w/t grows with α and there is no special change in the growth rate at the onset of buffet. The higher Mach numbers results in a thicker wake.

The effect of flap settings is shown in Figure 60 for M = 0.723. Positive flap angle increases w/t while negative flap angle gives a smaller value of w/t. At this Mach number, the wake thickness increases quite uniformly over the range of angle of incidence covered in the test. At off design Mach numbers, Figures 61 and 62 show the variation of w/t with α for M = 0.673 and 0.772.

4.0 Conclusions

A 16% thick supercritical airfoil with a trailing edge flap was tested in the NAE Two Dimensional Test Facility at a chord Reynolds number of 20 million. The investigation was carried out quite deep into the buffet régime and the effects of flaps on lift increments and buffet severity were analyzed. The results can be summarized as follows:

a) The onset of buffet can be determined quite accurately from plots of C_N' versus C_L at values of C_L where the slope of the curves is 0.1. For those conditions where buffet onset is primarily due to trailing edge separation, this value for the slope is found to

give consistent results which agree quite well with values computed from the criterion using the trailing edge pressure divergence.

Buffet boundaries can be raised appreciably for positive trailing edge flap deflections. Unlike conventional airfoils where regions of mild, moderate or heavy buffeting can be classified, the buffet onset boundaries for supercritical airfoils for $M < M_{DES}$ occur very close to and in some cases correspond to $C_{L_{max}}$. To identify regions of different degree of severity is often not possible. This suggests that the design condition for supercritical airfoils should be further away from the buffet boundary than the usual criteria used for conventional airfoils would indicate.

b) The shock positions and strengths are determined from the C_p measurements. For Mach numbers near or less than the design value the shock initially moves downstream with increasing angle of incidence to a maximum downstream position before moving slowly back upstream or, in some cases, remains more or less stationary. For higher Mach numbers, only upstream motion of the shock is detected and the flap settings do not have much influence on the shock location. For the lower Mach numbers, positive flap angles cause the shock to move further downstream, while the opposite is true for negative flap deflections.

The shock strength increases with incidence irrespective of whether the shock moves upstream or downstream. Positive flap angles increase the strength but the effect is small at higher Mach numbers.

Spectral analyses of the balance normal force outputs show shock oscillations at about 70 Hz for this airfoil. The fluctuations are largest at values of Mach numbers near the design value, beyond which a sharp drop in the buffet boundaries occurs. Slightly inside the buffet régime, the magnitudes of the fluctuating normal force have quite large values near the "elbow" of the

buffet onset curve. As the Mach number increases to higher values, the fluctuations in normal force decreases and the shock waves become more steady.

c) Intrusion into the buffet régime and the resulting buffet severity can be indicated either by the decrease in trailing edge pressure $\Delta C_{P_{TE}}$ or increase in magnitude of the fluctuating normal force $\Delta C'_N$. For Mach numbers near the design value, much larger changes in $\Delta C'_N$ with $\Delta C_{P_{TE}}$ are observed than for other values of M.

d) At the design $C_L = 0.6$, small flap angles do not increase the drag significantly. For off design conditions the drag rise is much larger for negative flap angles than for positive angles of the same magnitude. The wake profiles show large unsteady fluctuations at conditions beyond the buffet onset boundary. Near the design Mach number, positive flap angles increase the wake thickness while negative angles have the opposite effect. The growth of the width of the wake is quite uniform over the range of angle of incidence covered in the test. In most cases drag increases significantly before buffet onset.

5.0 References

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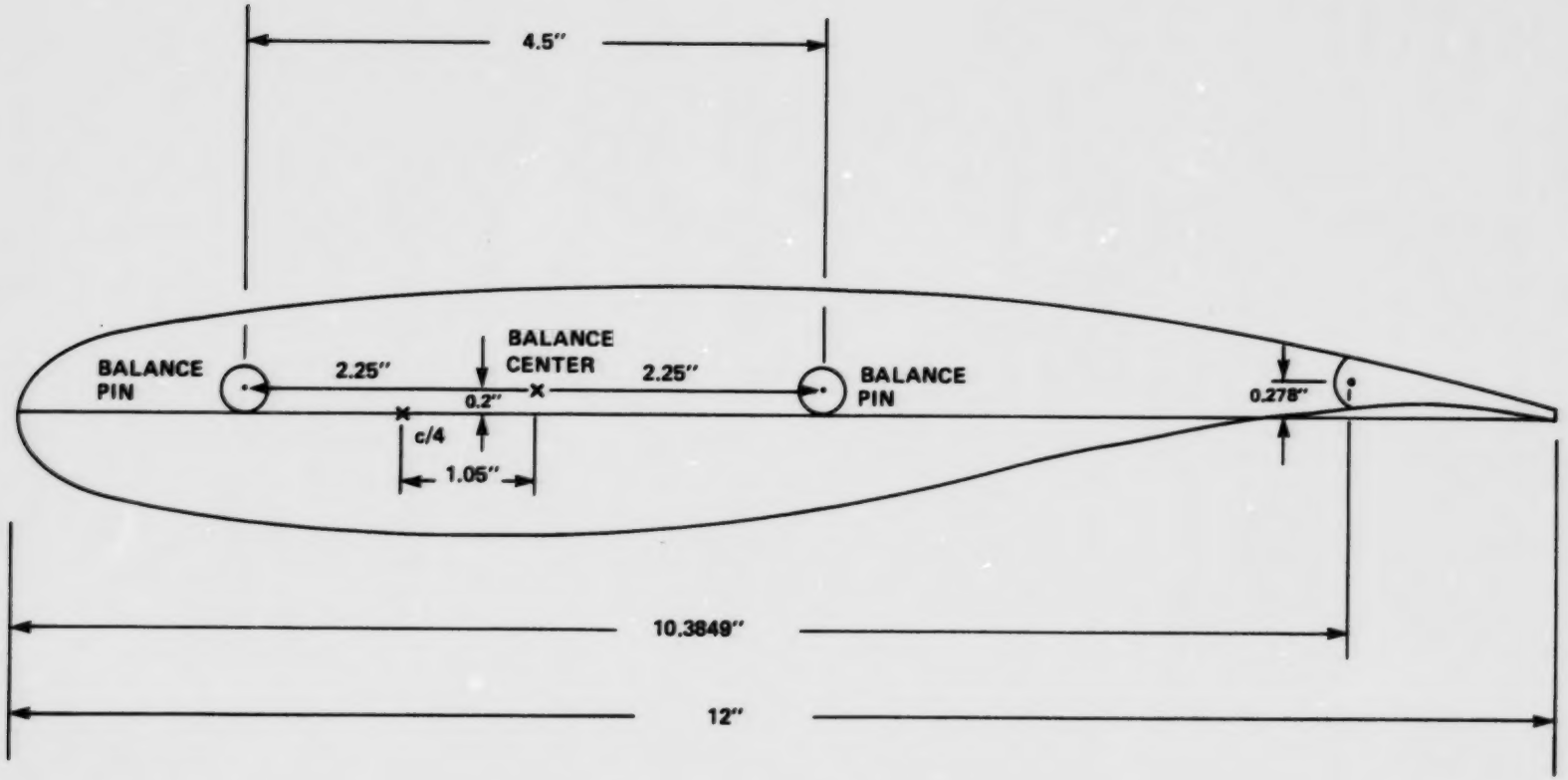

FIG. 1: SCHEMATIC OF SUPERCRITICAL AIRFOIL WITH 16% THICKNESS TO CHORD RATIO

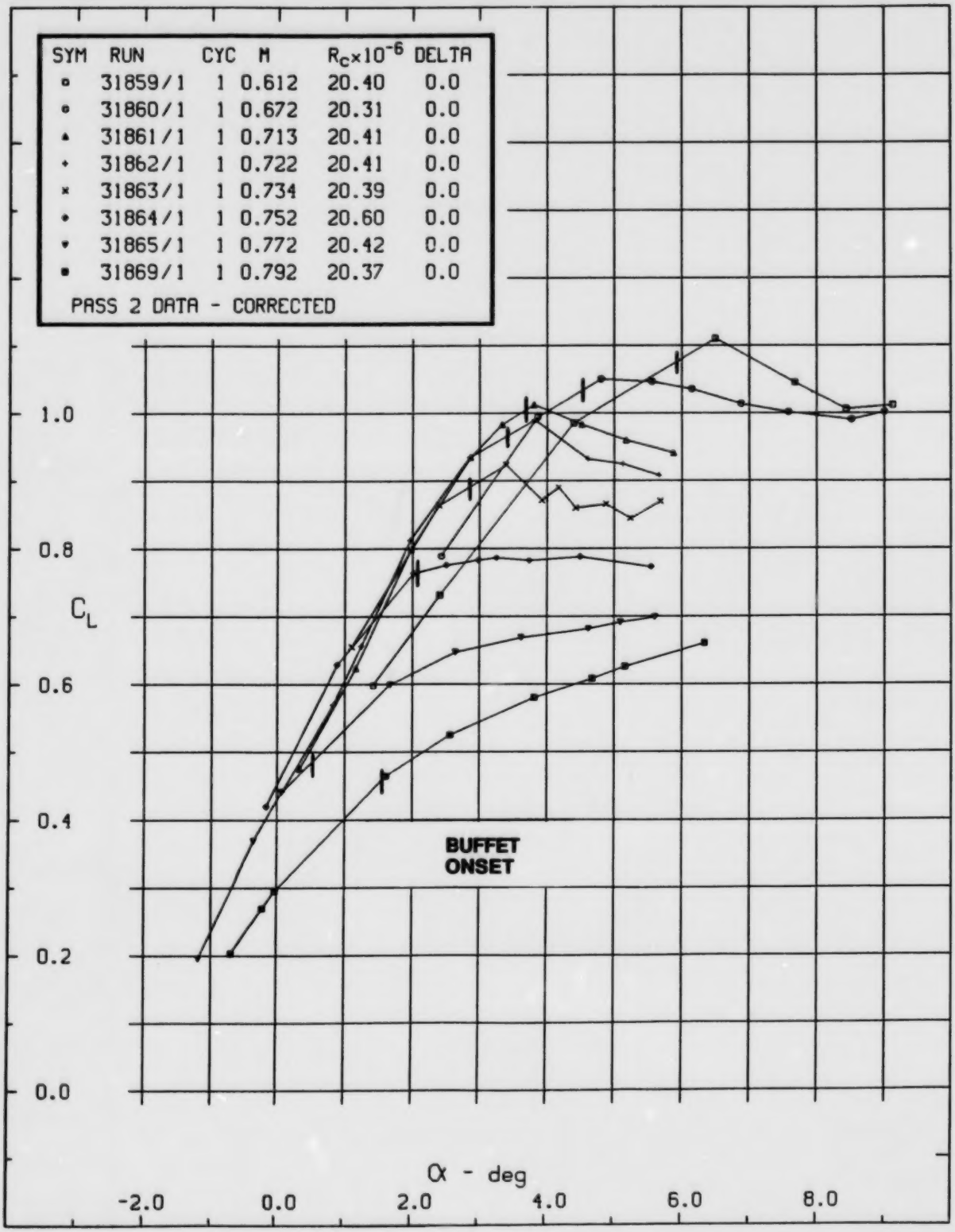

FIG. 2: LIFT VERSUS ANGLE OF INCIDENCE AT VARIOUS MACH NUMBERS FOR FLAP ANGLE $\delta = 0°$

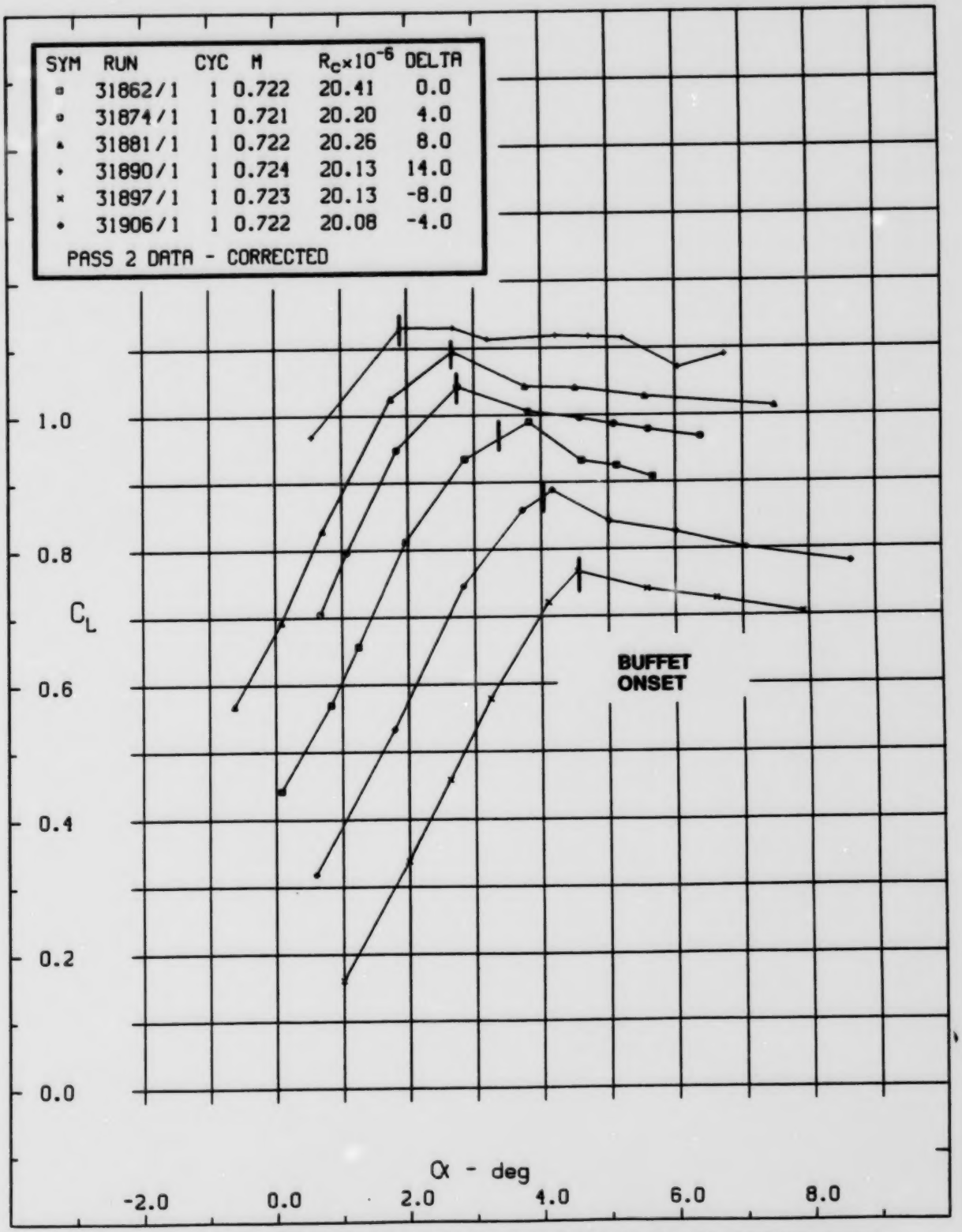

FIG. 3: LIFT VERSUS ANGLE OF INCIDENCE AT M ABOUT 0.723 FOR VARIOUS FLAP ANGLES

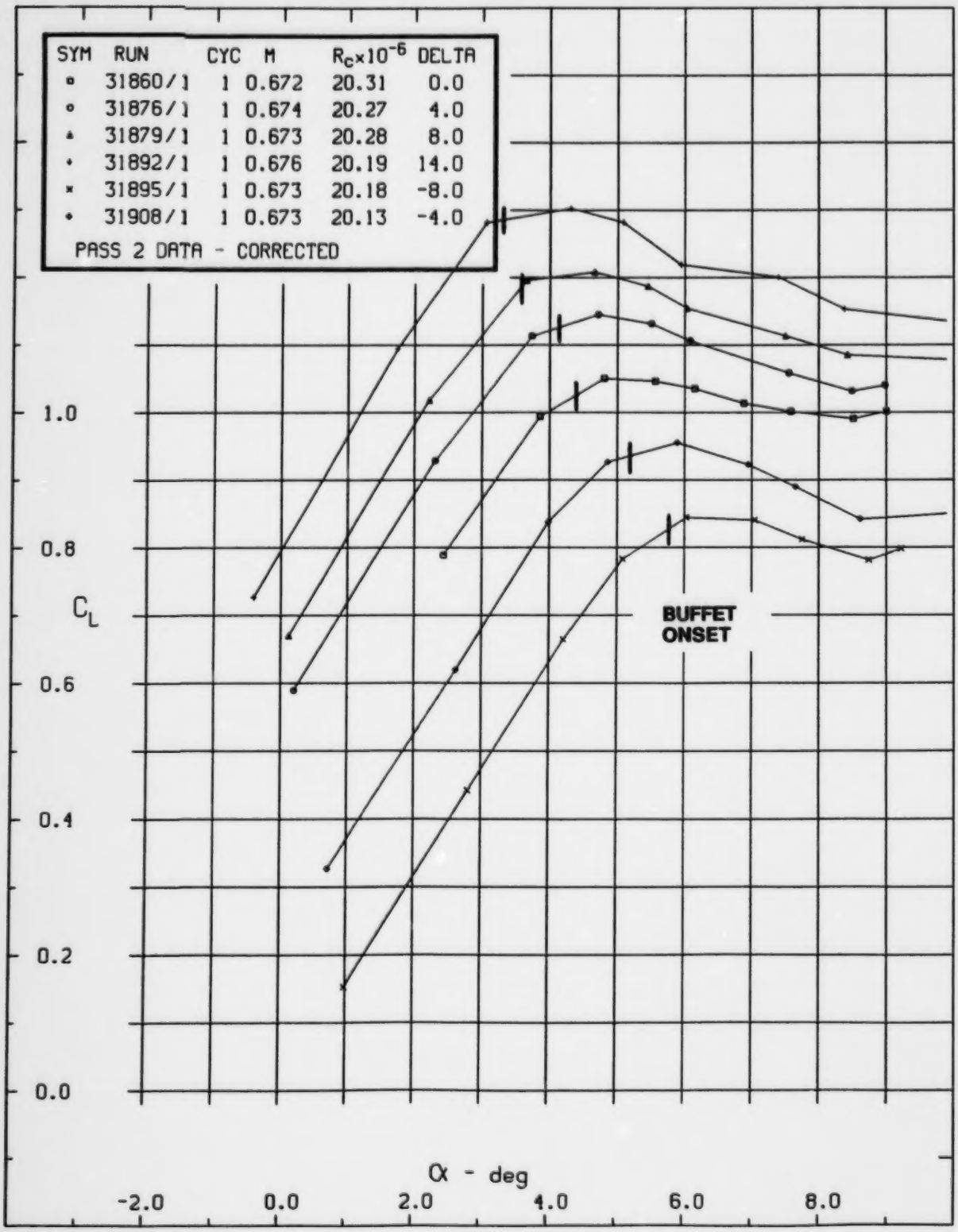

FIG. 4: LIFT VERSUS ANGLE OF INCIDENCE AT M ABOUT 0.673 FOR VARIOUS FLAP ANGLES

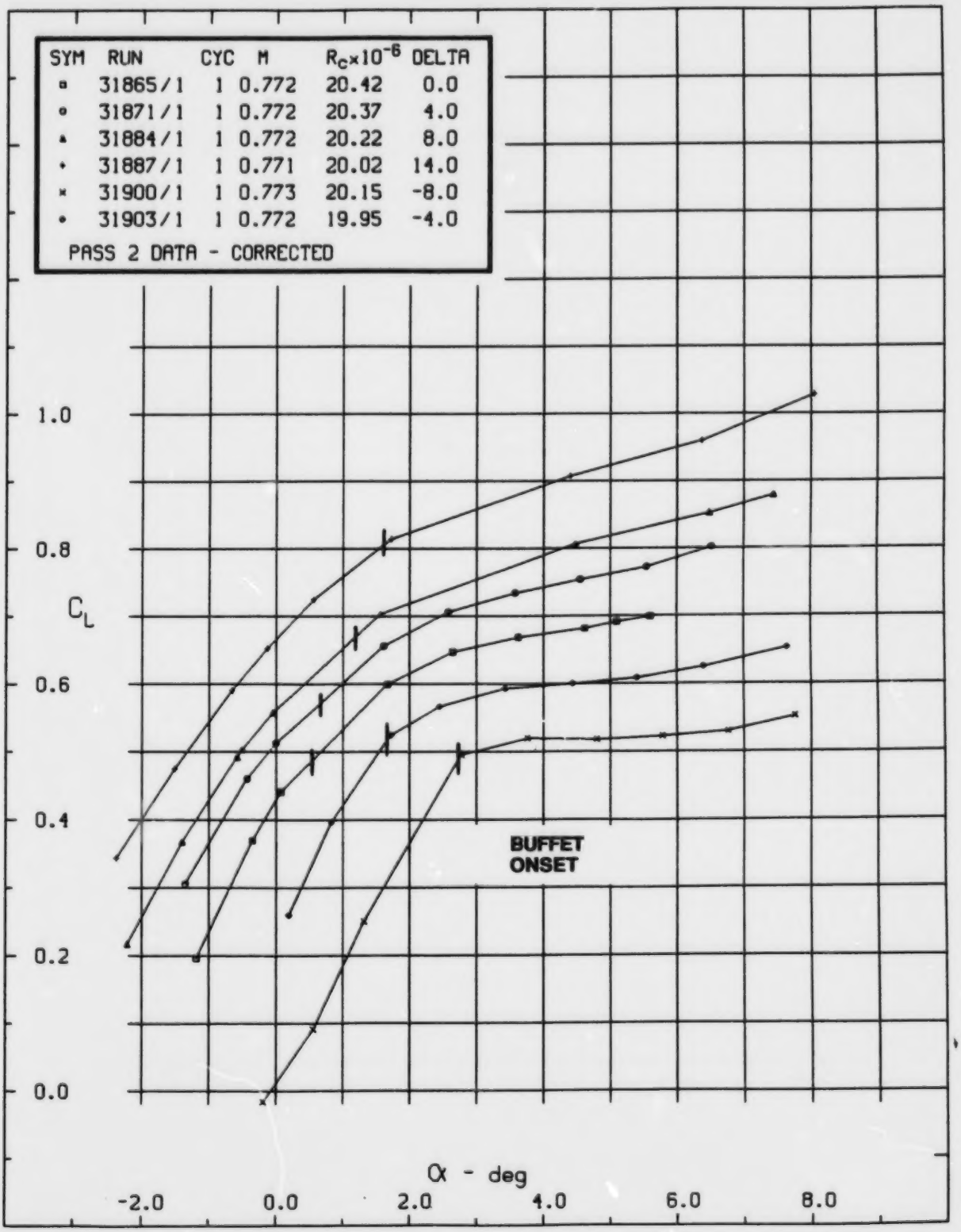

FIG. 5: LIFT VERSUS ANGLE OF INCIDENCE AT M ABOUT 0.772 FOR VARIOUS FLAP ANGLES

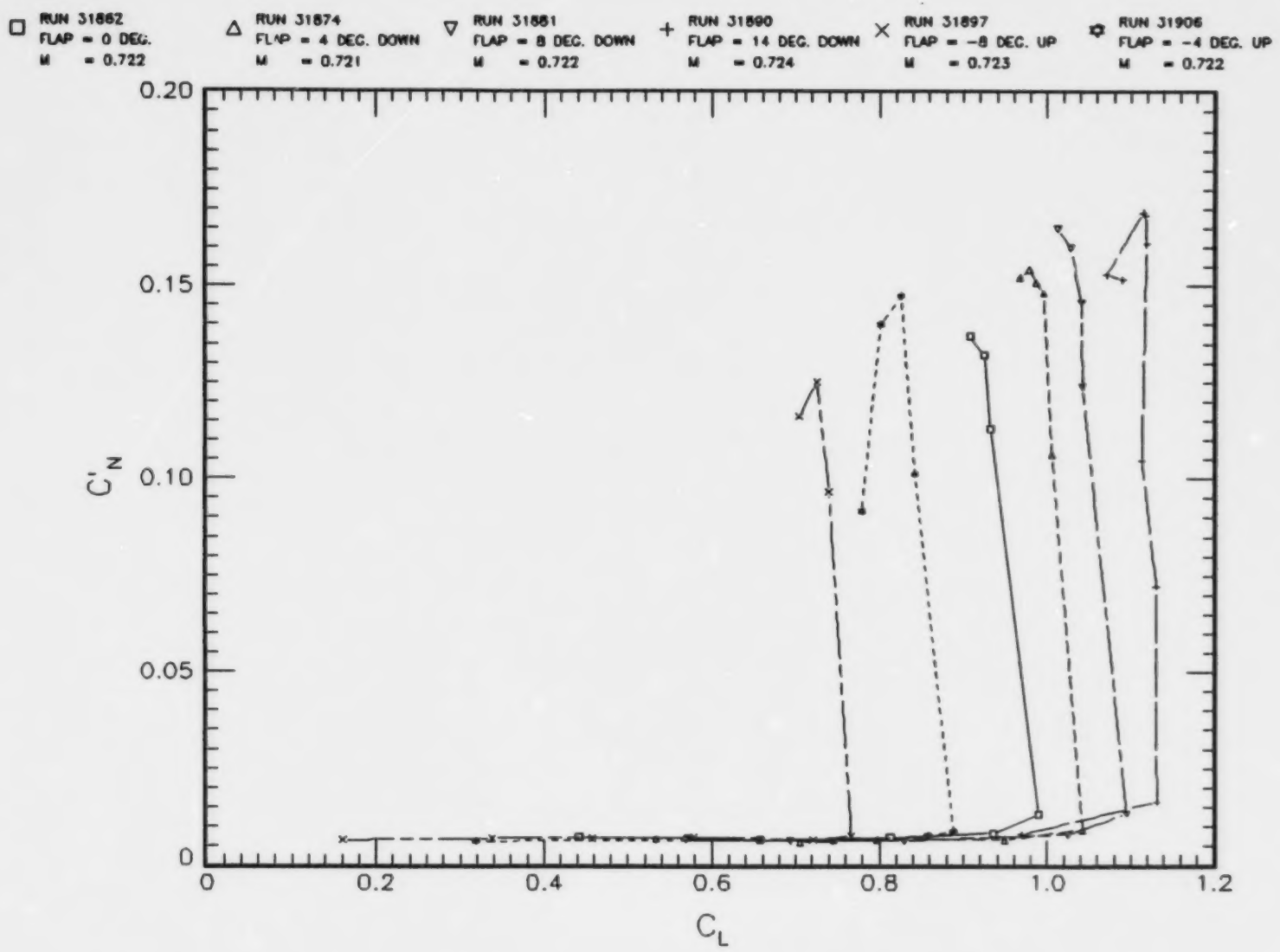

FIG. 6: NORMAL FORCE FLUCTUATIONS VERSUS LIFT AT M ABOUT 0.723 FOR VARIOUS FLAP ANGLES

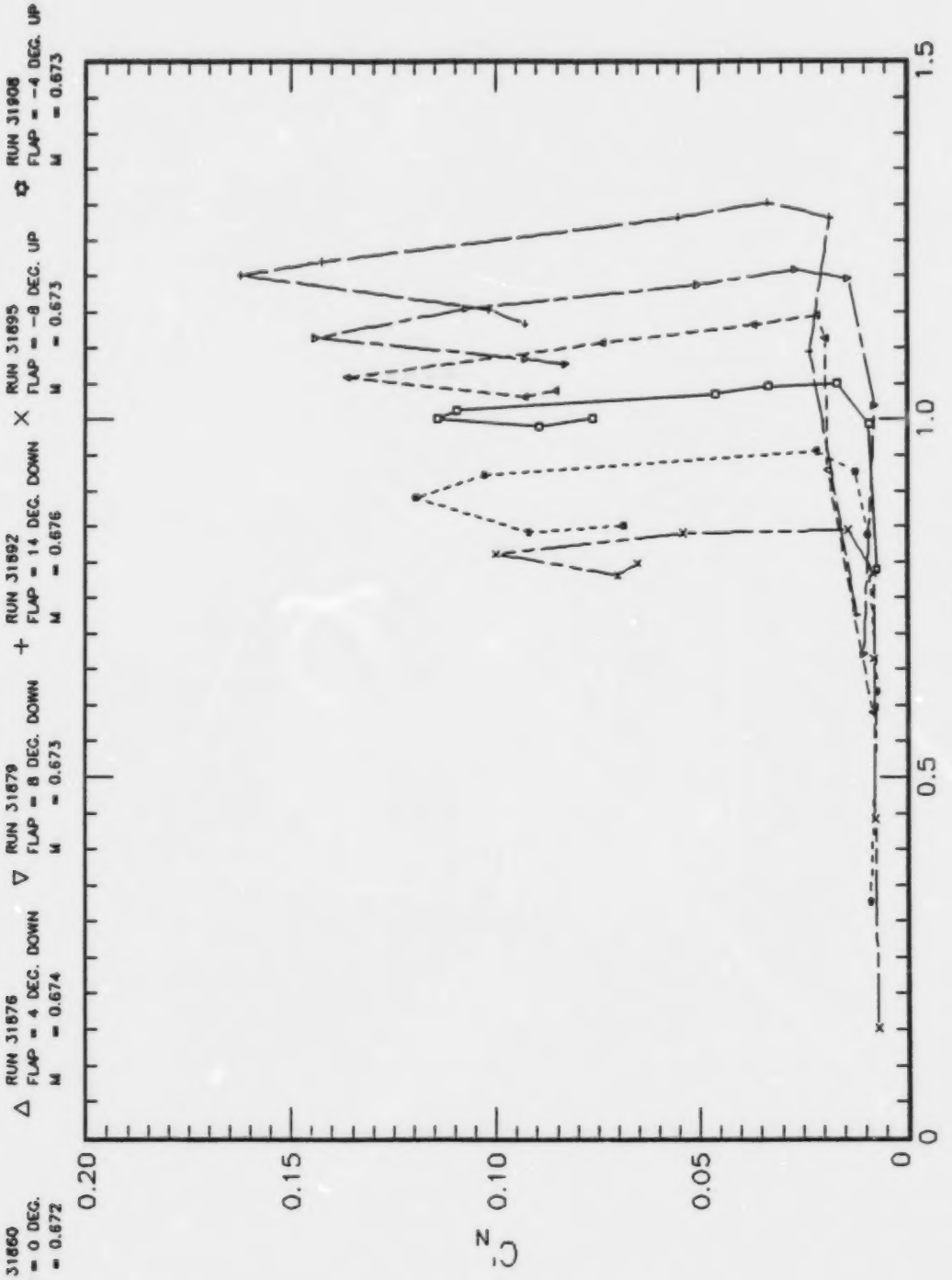

FIG. 7: NORMAL FORCE FLUCTUATIONS VERSUS LIFT AT M ABOUT 0.673 FOR VARIOUS FLAP ANGLES

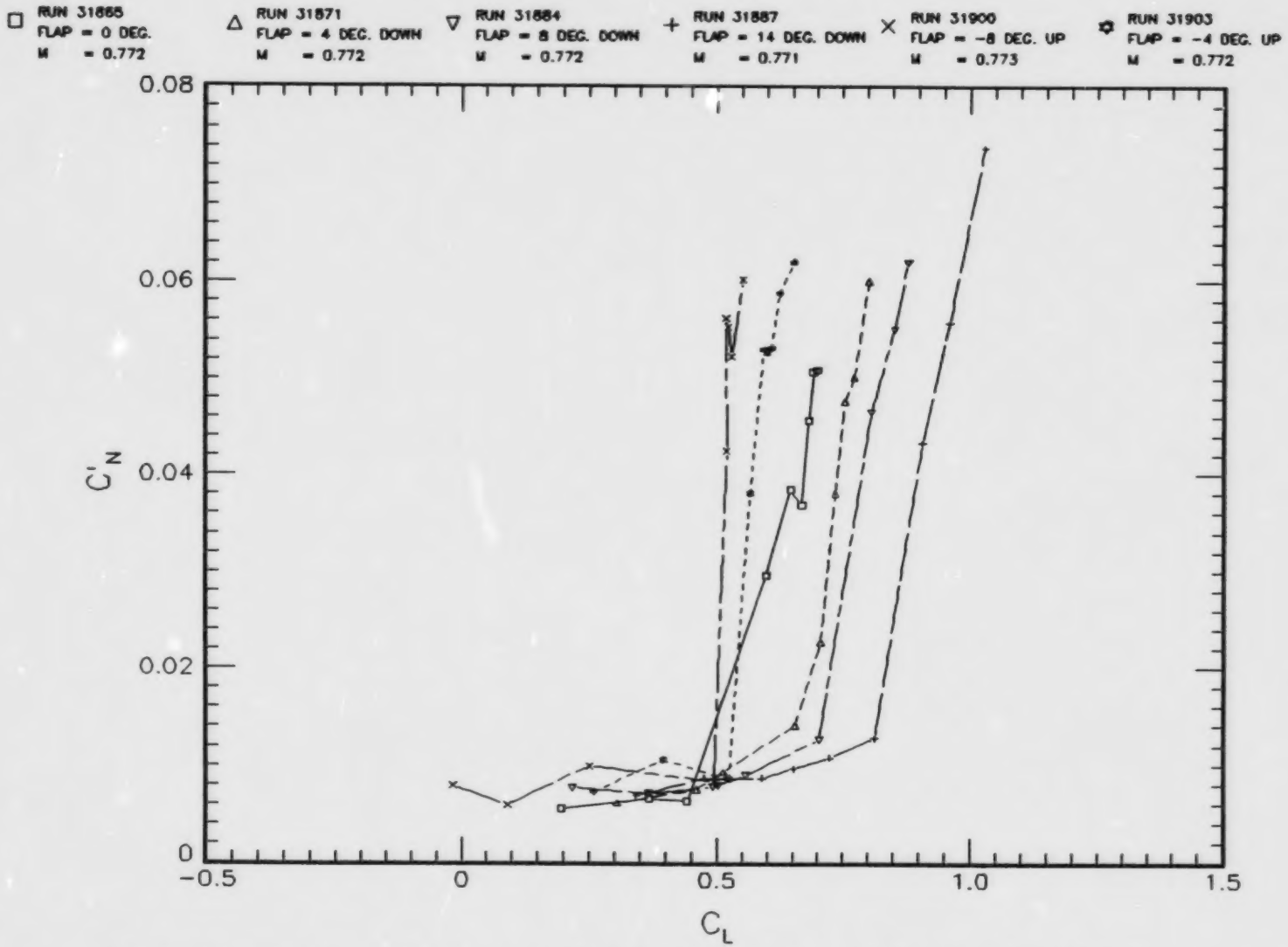

FIG. 8: NORMAL FORCE FLUCTUATIONS VERSUS LIFT AT M ABOUT 0.772 FOR VARIOUS FLAP ANGLES

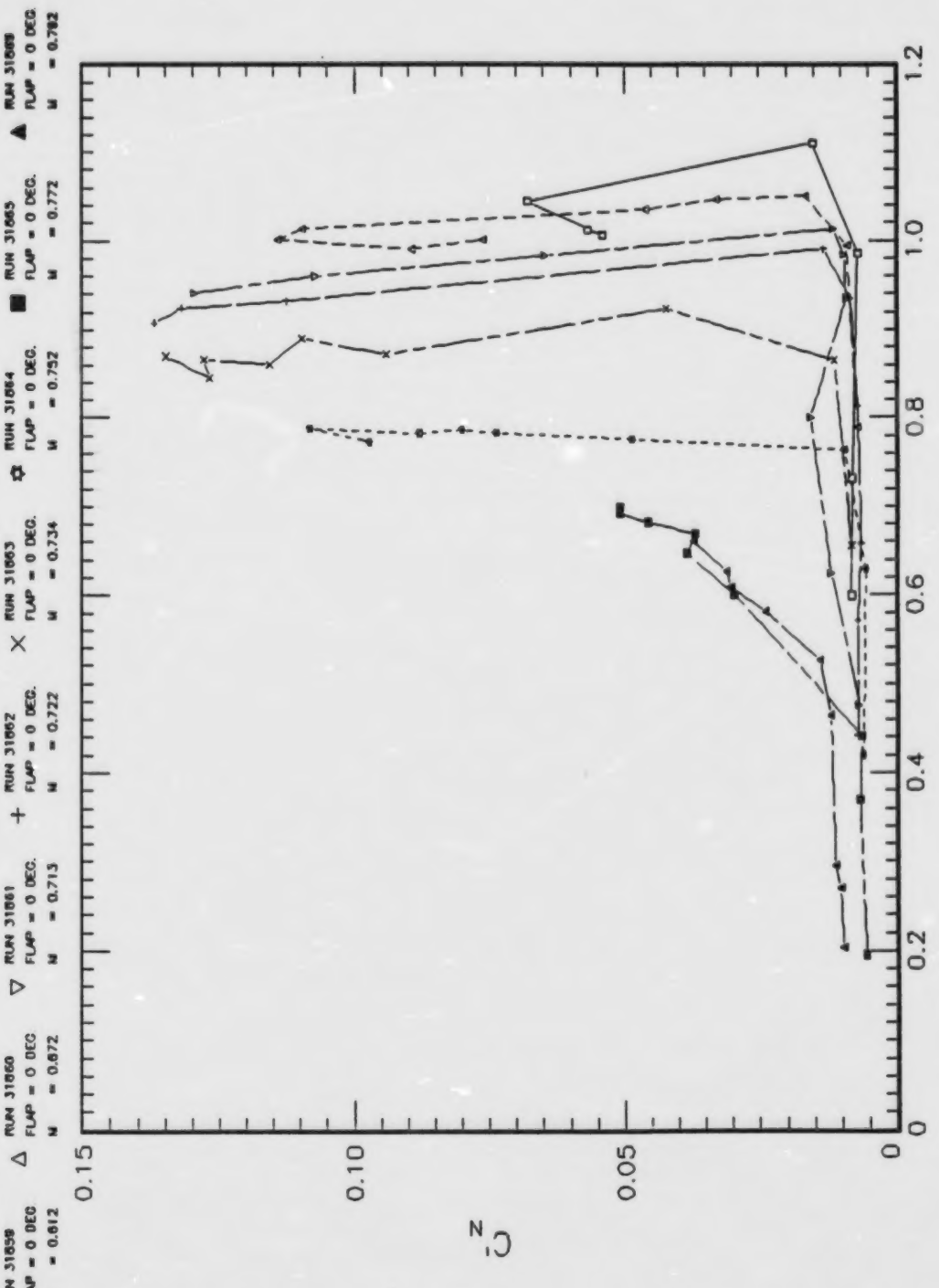

FIG. 9: NORMAL FORCE FLUCTUATIONS VERSUS LIFT AT VARIOUS MACH NUMBERS FOR FLAP ANGLE $\delta = 0°$

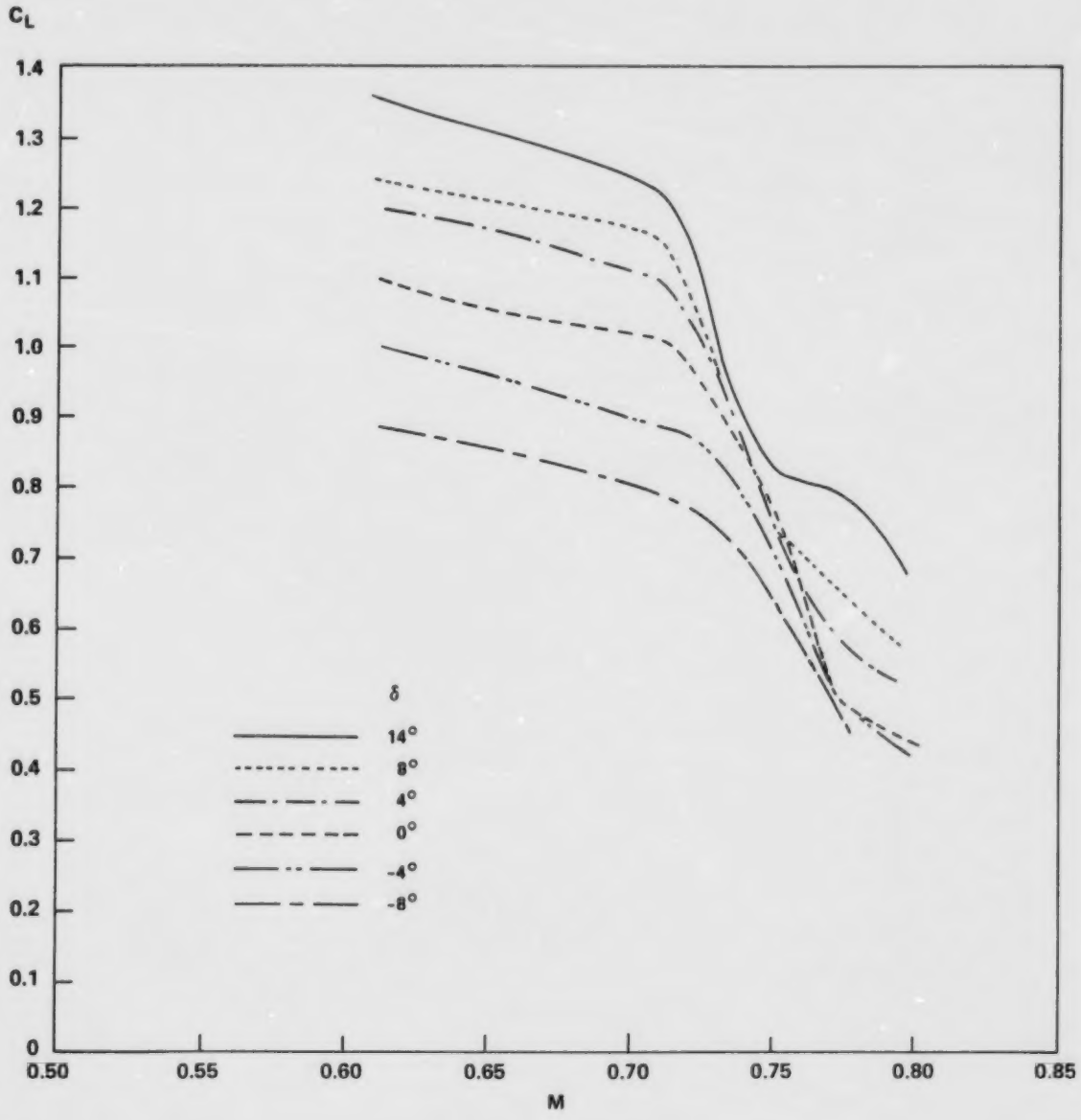

FIG. 10: LIFT VERSUS MACH NUMBER BUFFET BOUNDARIES FOR VARIOUS FLAP ANGLES

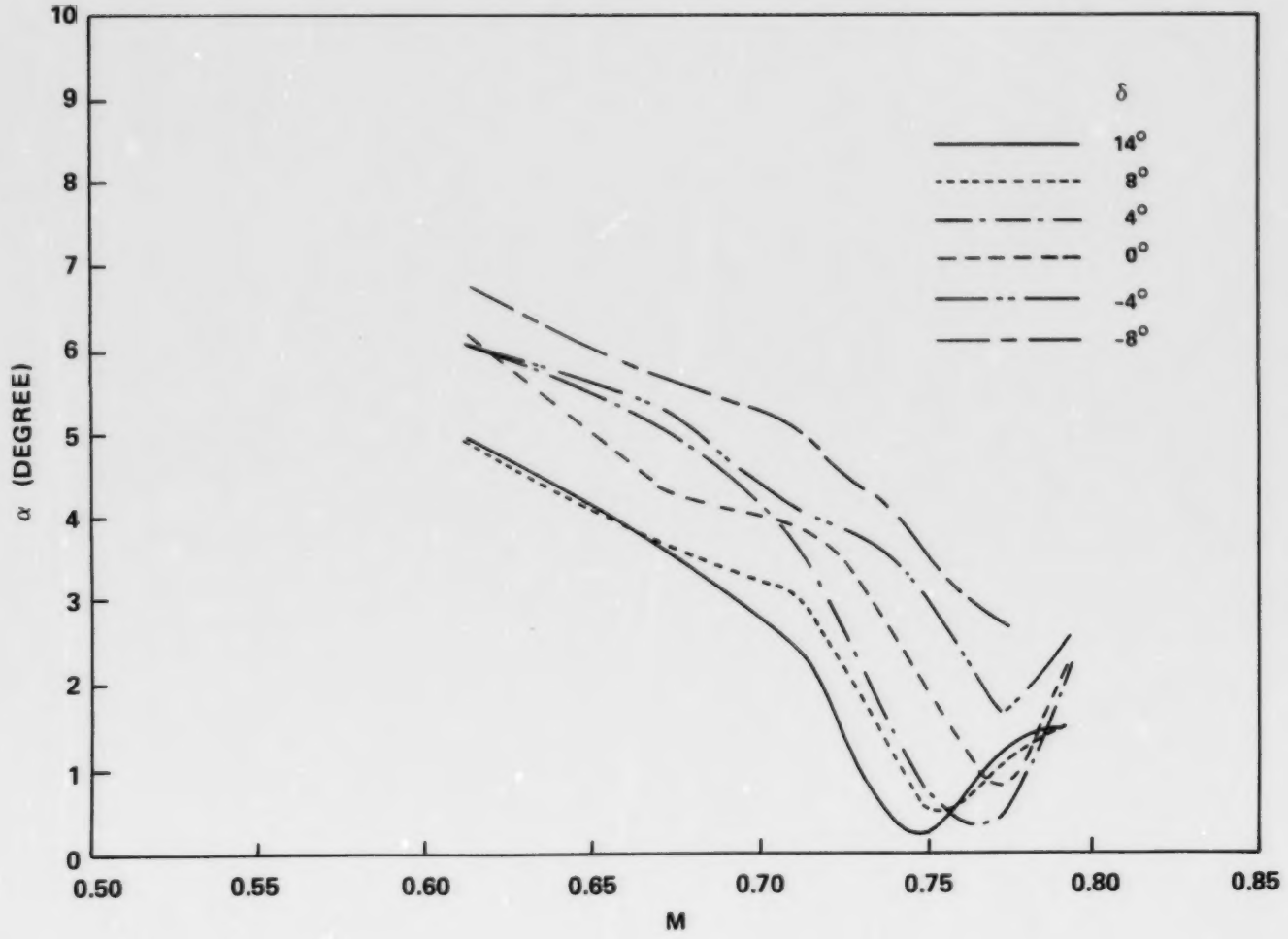

FIG. 11: ANGLE OF INCIDENCE VERSUS MACH NUMBER BUFFET BOUNDARIES FOR VARIOUS FLAP ANGLES

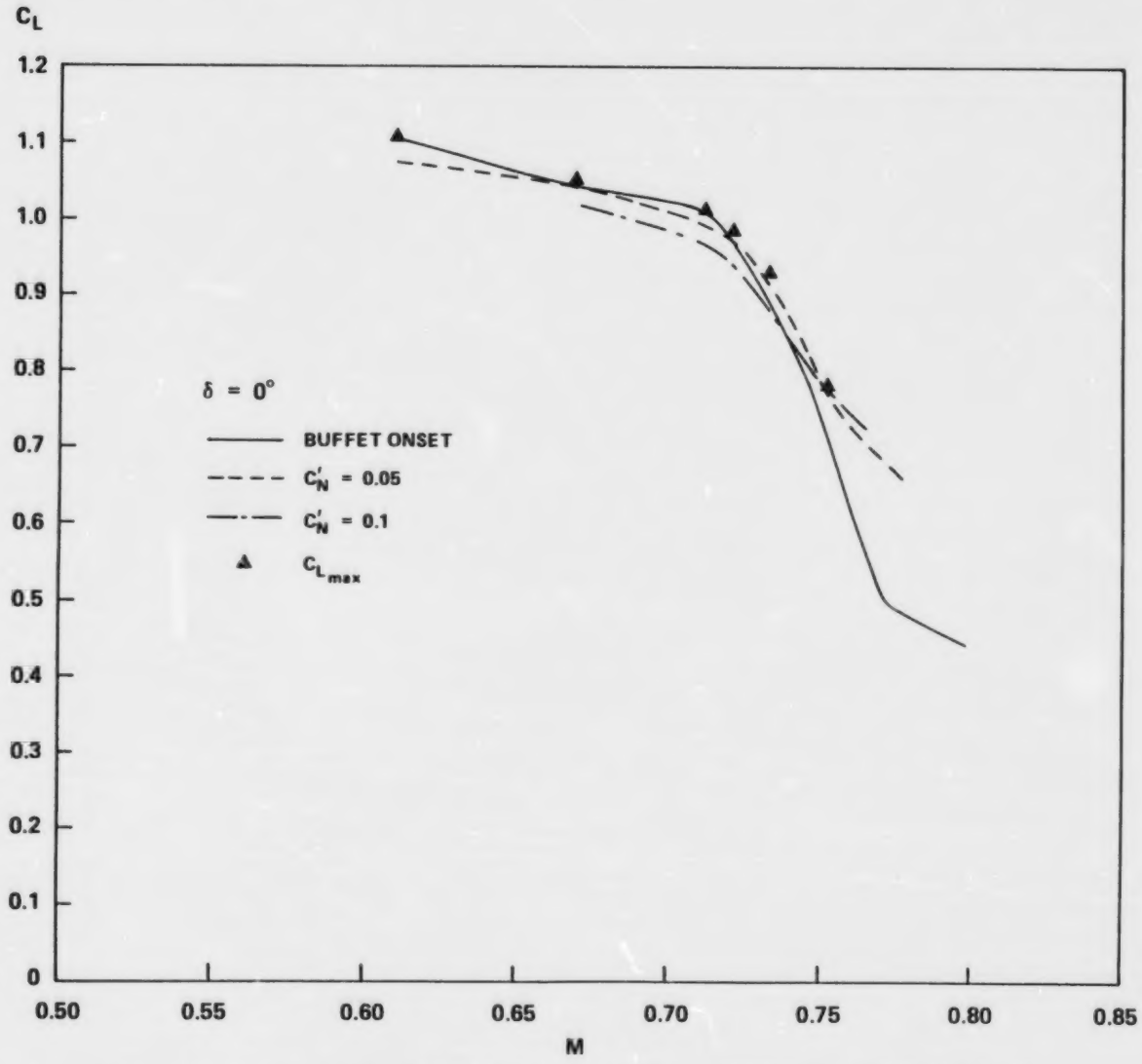

FIG. 12: LIFT VERSUS MACH NUMBER BUFFET BOUNDARIES WITH FLAP ANGLE δ = 0°

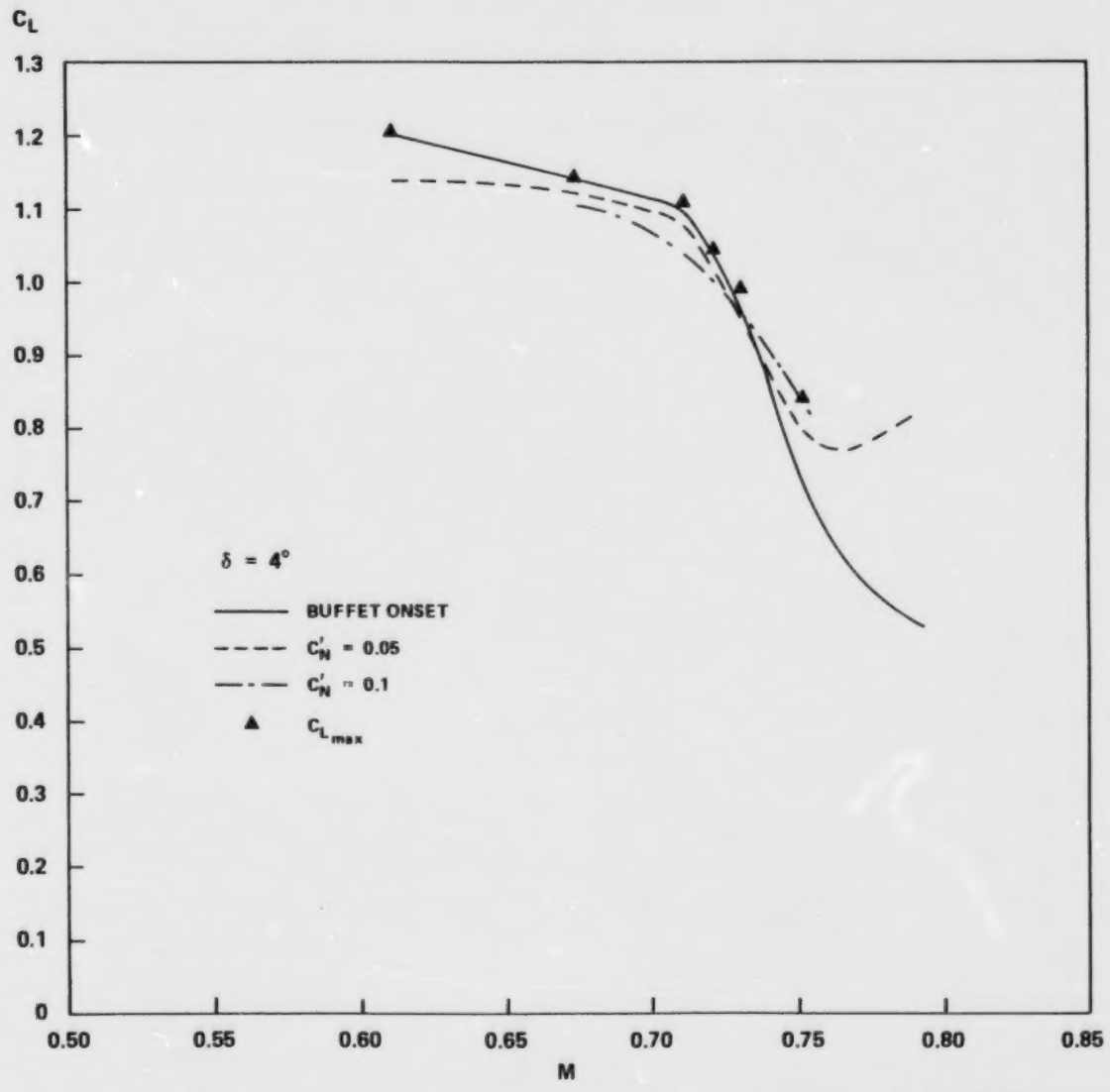

FIG. 13: LIFT VERSUS MACH NUMBER BUFFET BOUNDARIES WITH FLAP ANGLE δ = 4°

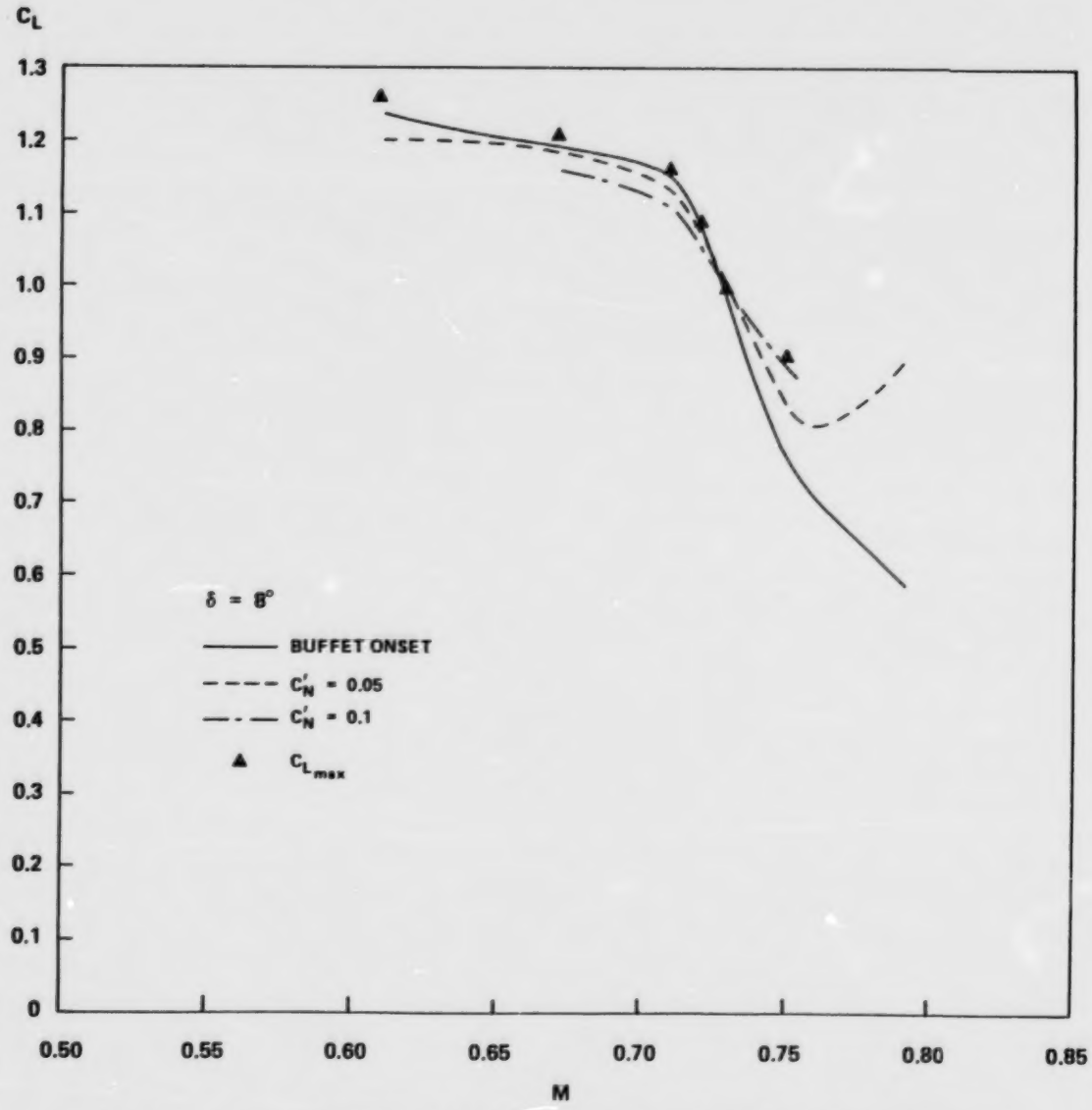

FIG. 14: LIFT VERSUS MACH NUMBER BUFFET BOUNDARIES WITH FLAP ANGLE δ = 8°

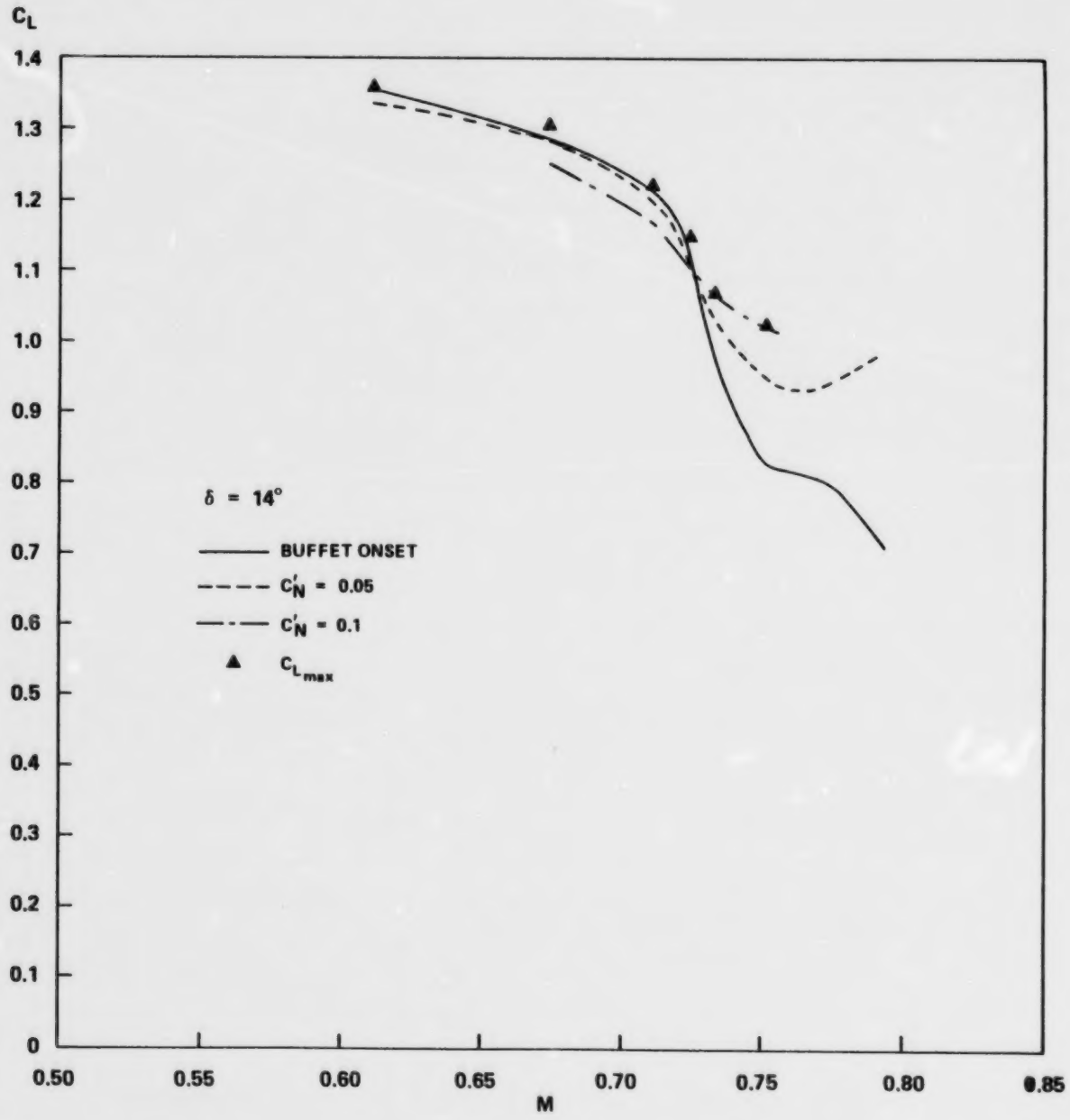

FIG. 15: LIFT VERSUS MACH NUMBER BUFFET BOUNDARIES WITH FLAP ANGLE δ = 14°

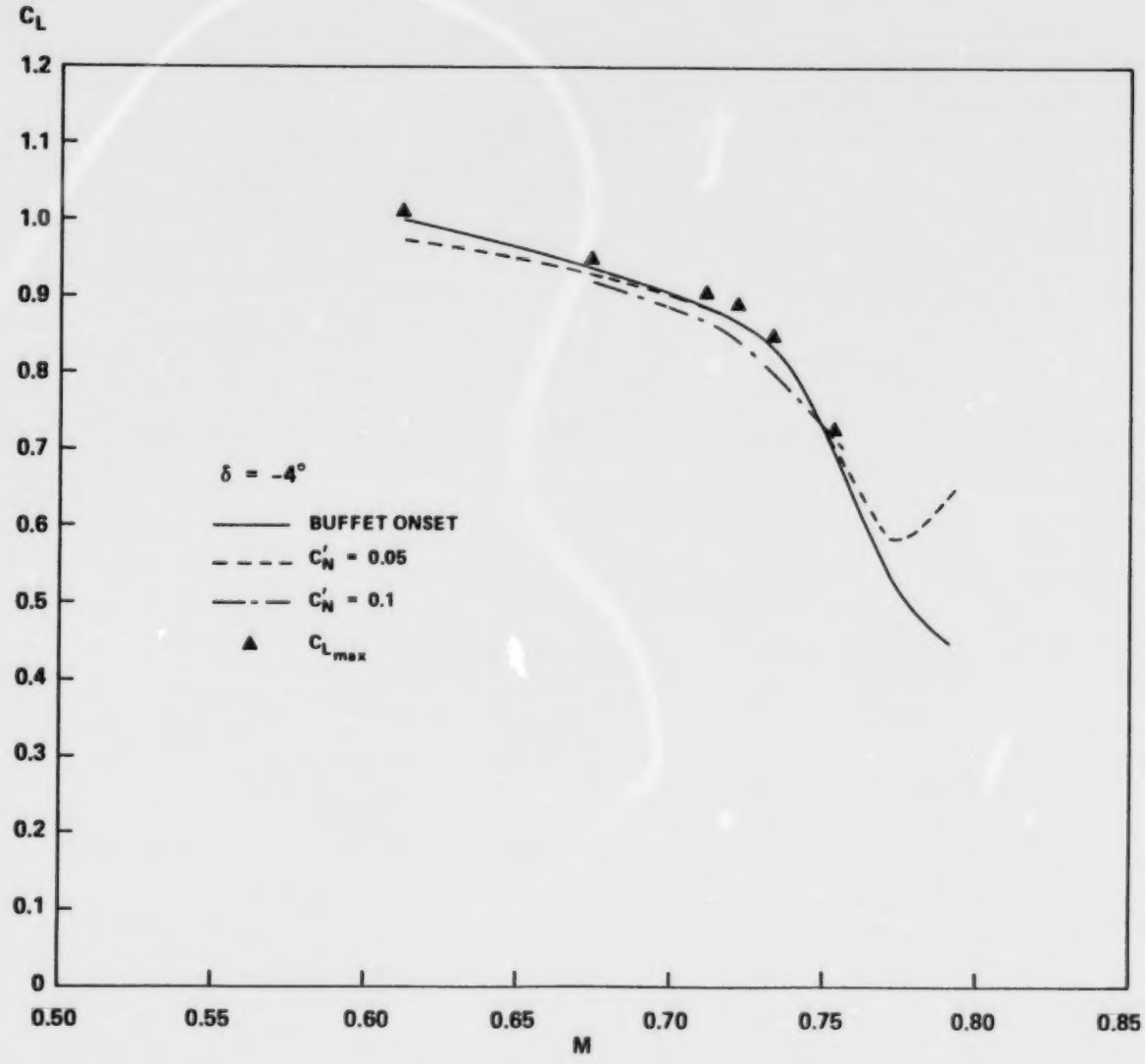

FIG. 16: LIFT VERSUS MACH NUMBER BUFFET BOUNDARIES WITH FLAP ANGLE δ = -4°

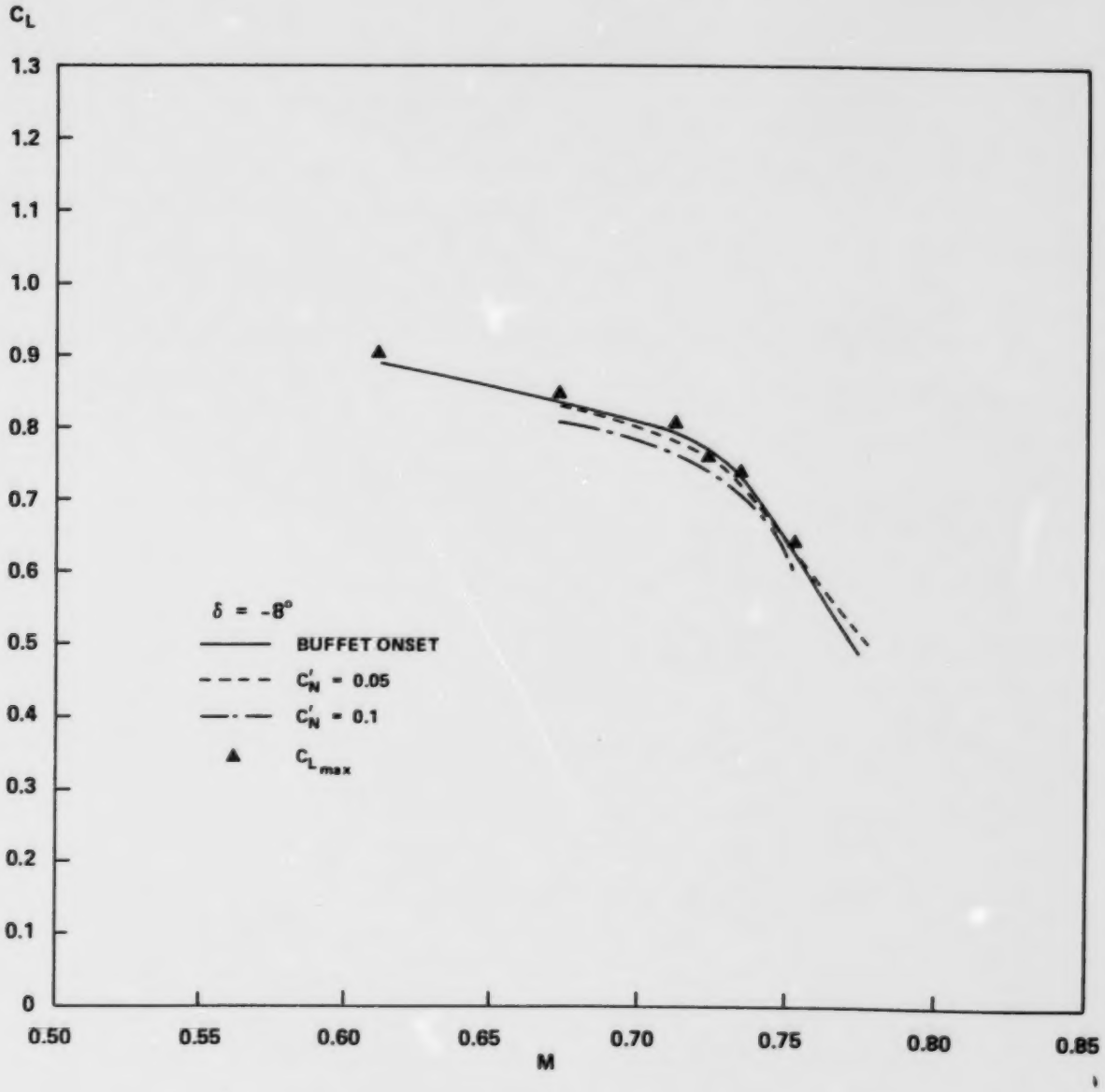

FIG. 17: LIFT VERSUS MACH NUMBER BUFFET BOUNDARIES WITH FLAP ANGLE δ = -8°

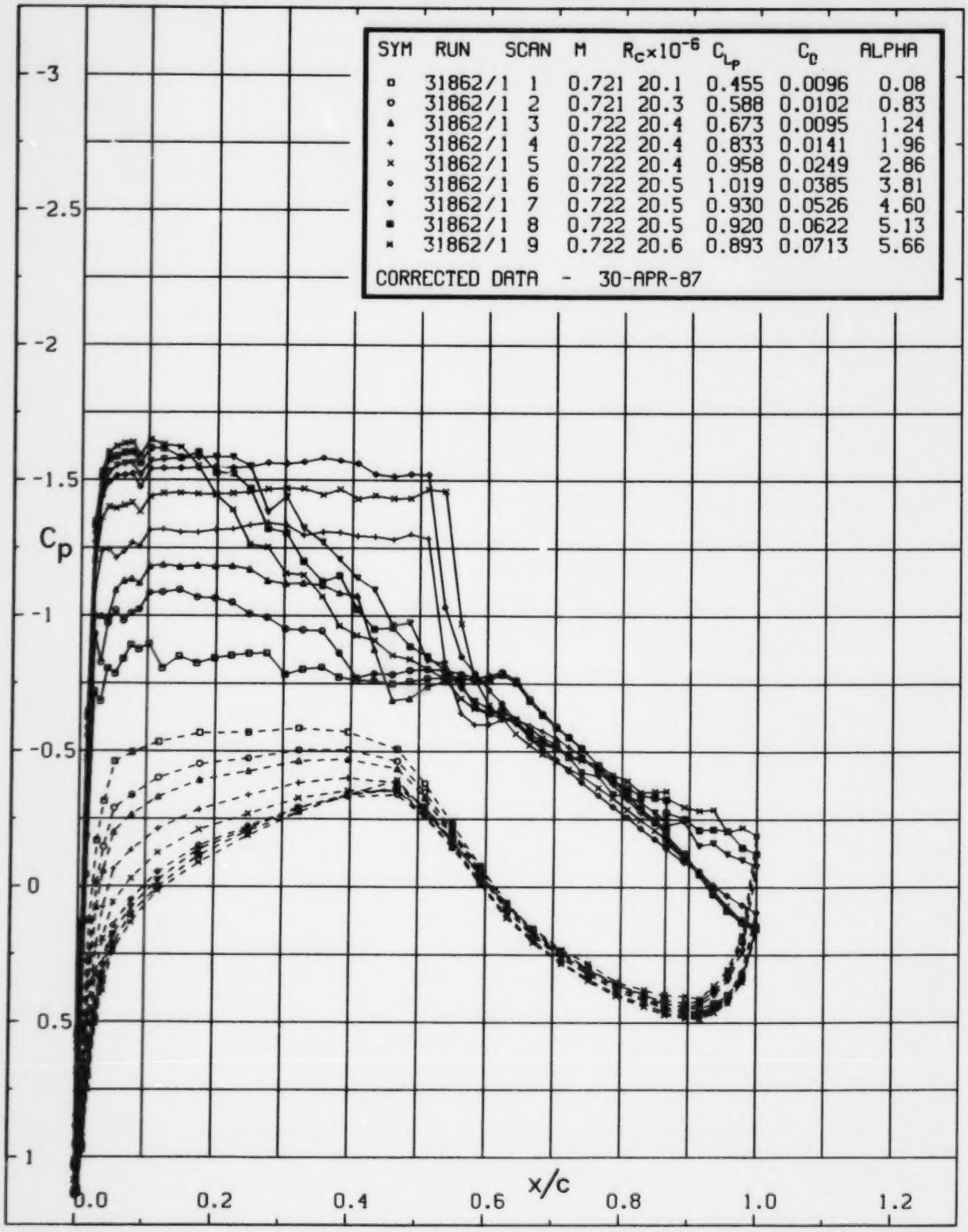

FIG. 18: SURFACE PRESSURE DISTRIBUTIONS AT M ABOUT 0.711 FOR FLAP ANGLE $\delta = 0°$

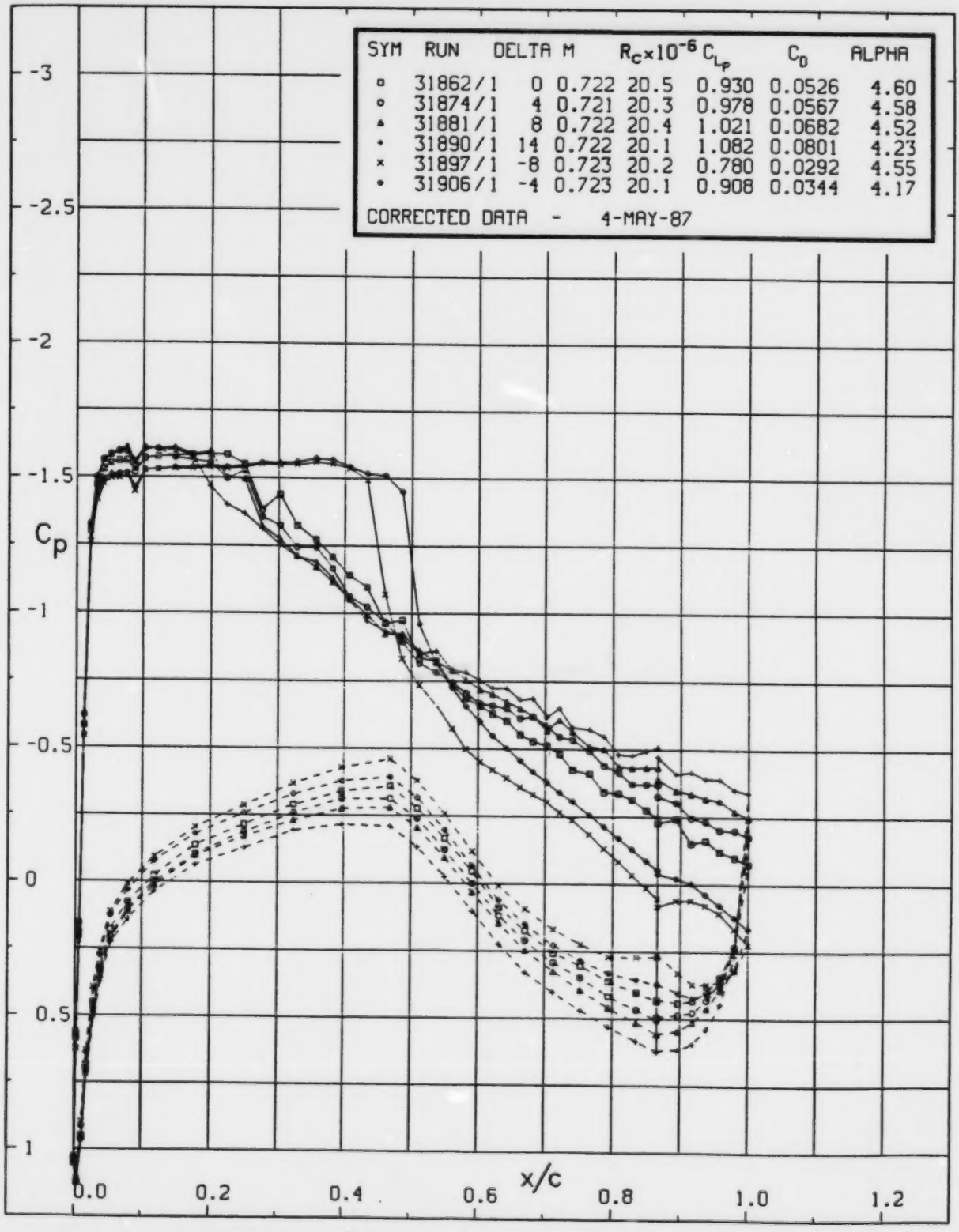

FIG. 19: SURFACE PRESSURE DISTRIBUTIONS AT M ABOUT 0.723 FOR VARIOUS FLAP ANGLES AT α ABOUT 4.5°

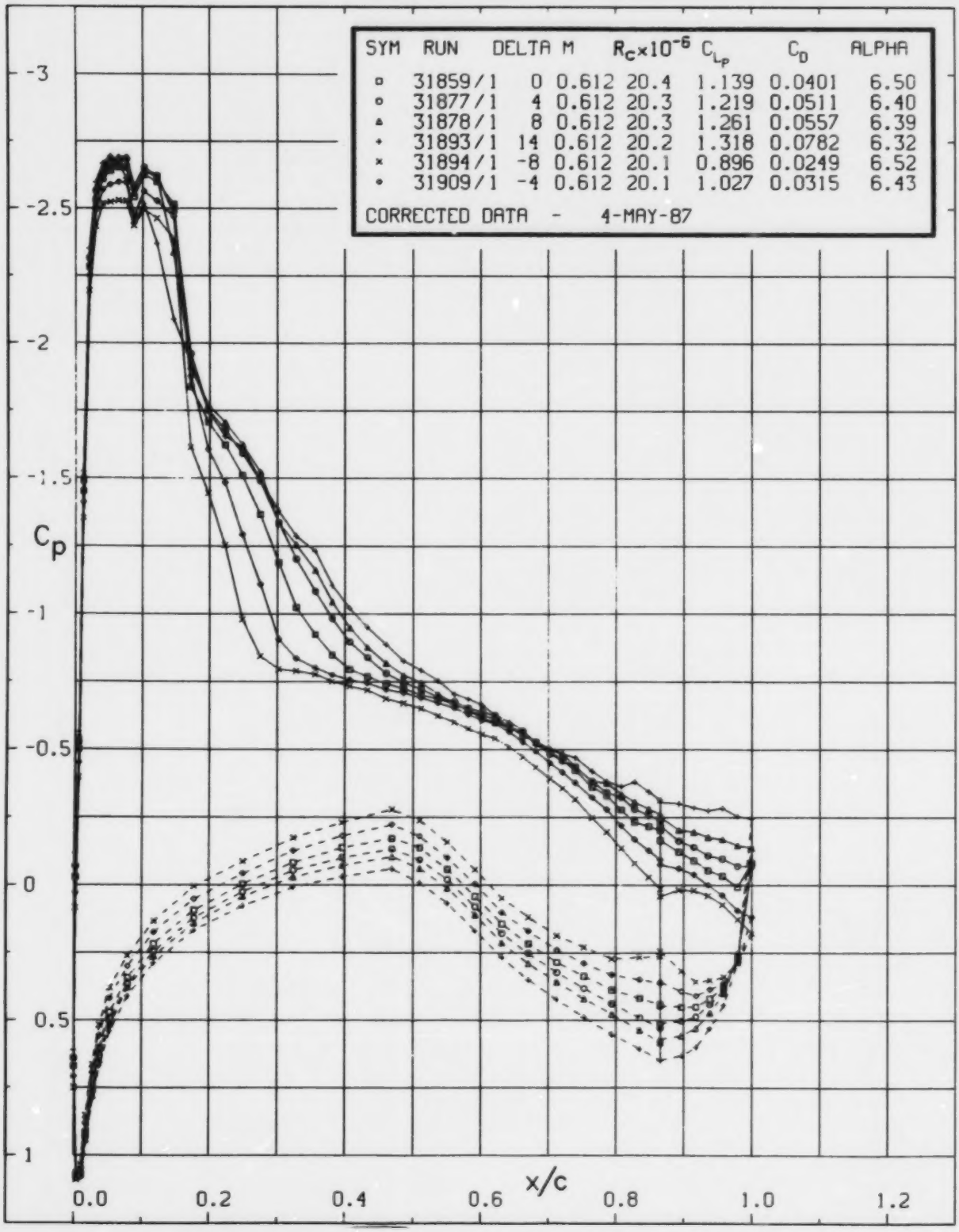

FIG. 20: SURFACE PRESSURE DISTRIBUTIONS AT M ABOUT 0.612 FOR VARIOUS FLAP ANGLES AT α ABOUT 6.5°

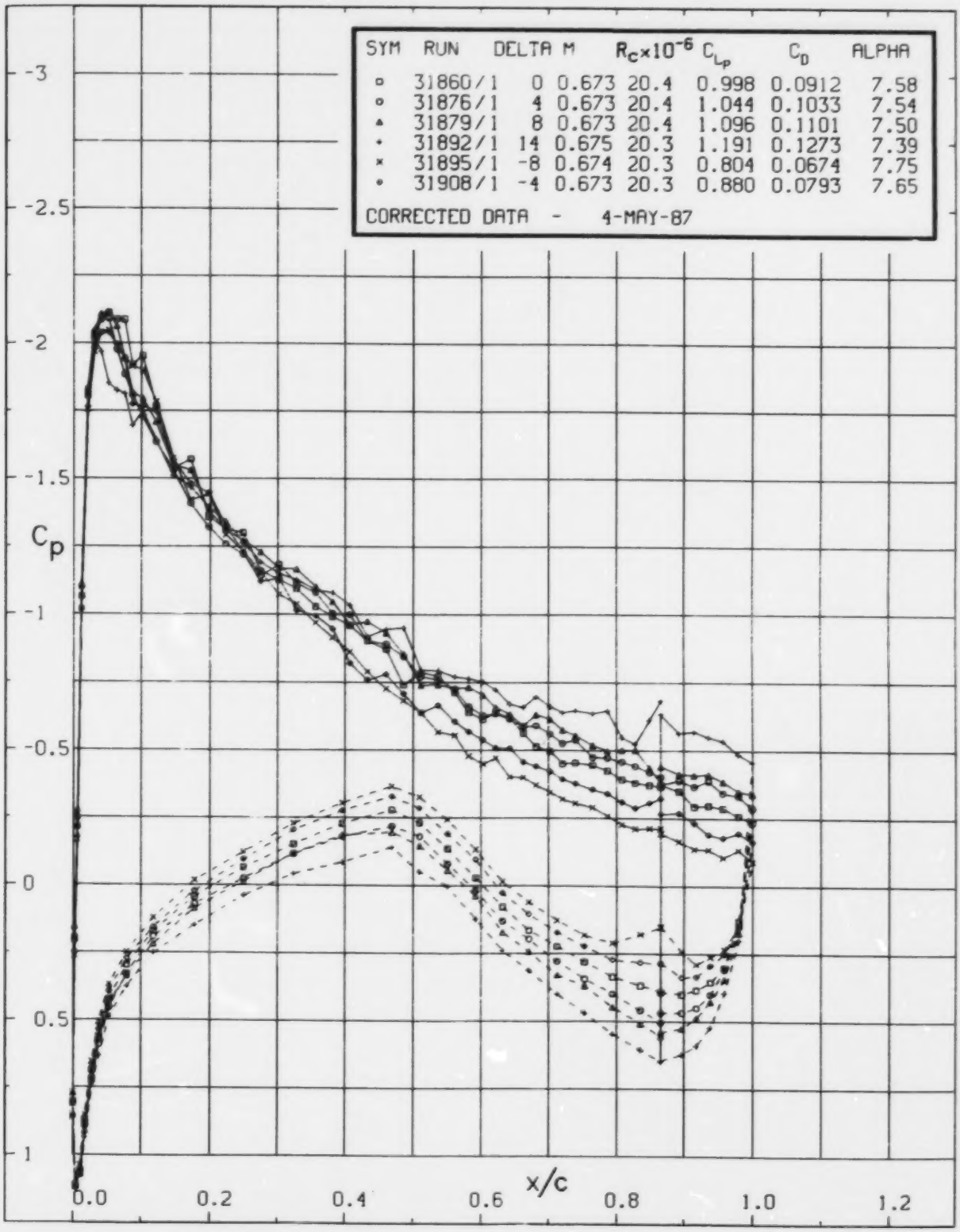

FIG. 21: SURFACE PRESSURE DISTRIBUTIONS AT M ABOUT 0.673 FOR VARIOUS FLAP ANGLES AT α ABOUT 7.5°

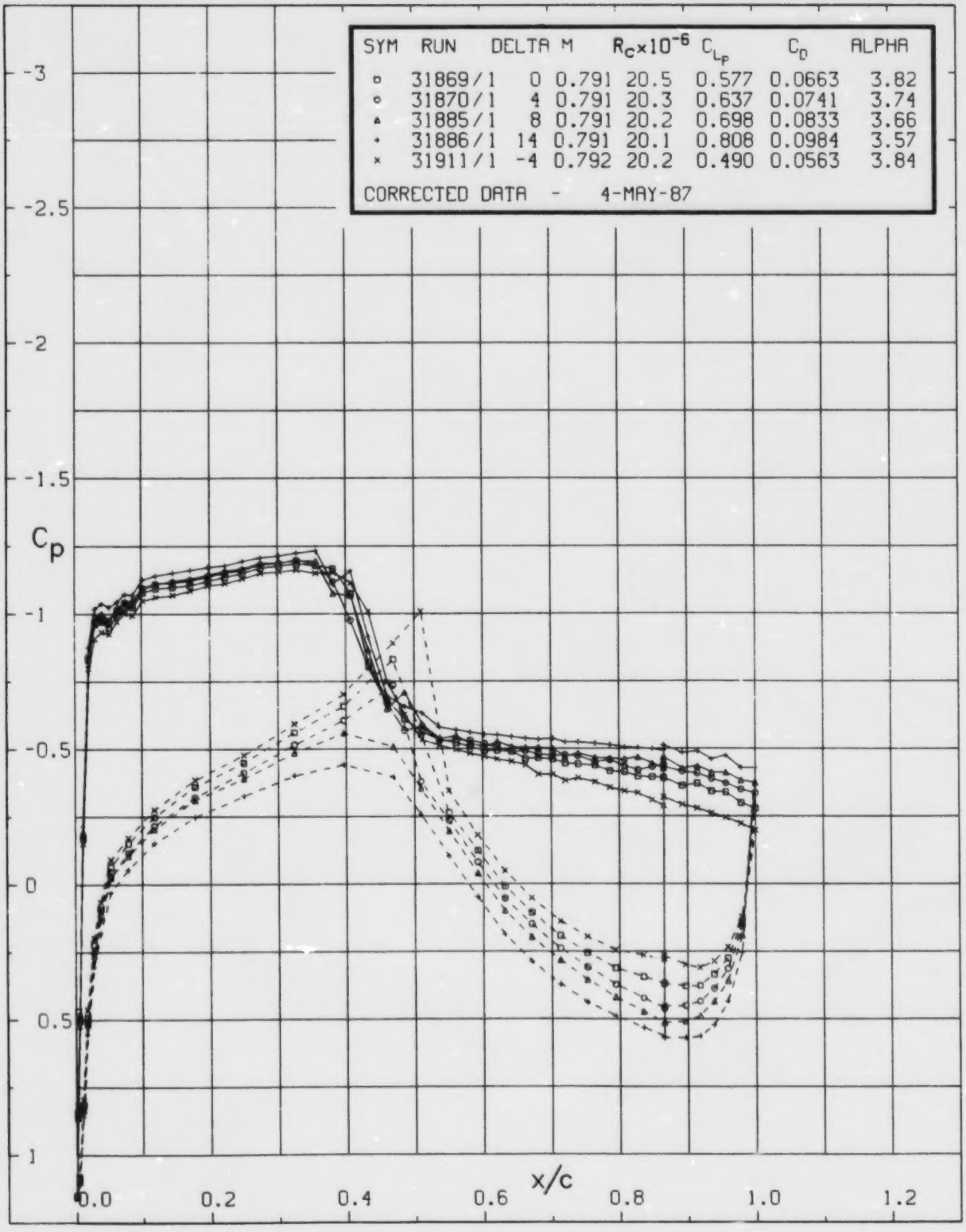

FIG. 22: SURFACE PRESSURE DISTRIBUTIONS AT M ABOUT 0.791 FOR VARIOUS FLAP ANGLES AT α ABOUT 3.75°

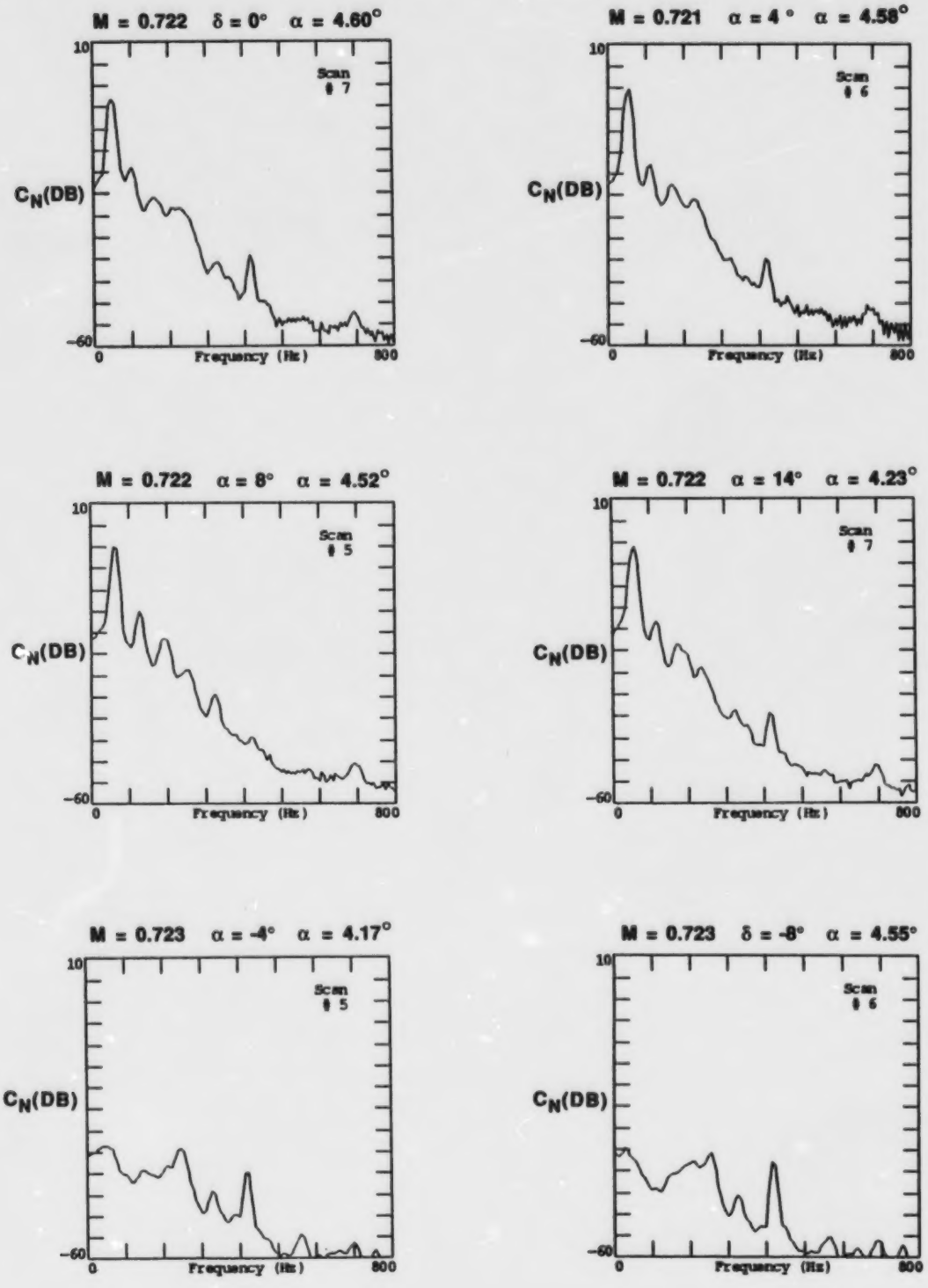

FIG. 23: POWER SPECTRA OF BALANCE NORMAL FORCE AT M ABOUT 0.723 AND α ABOUT 4.5°

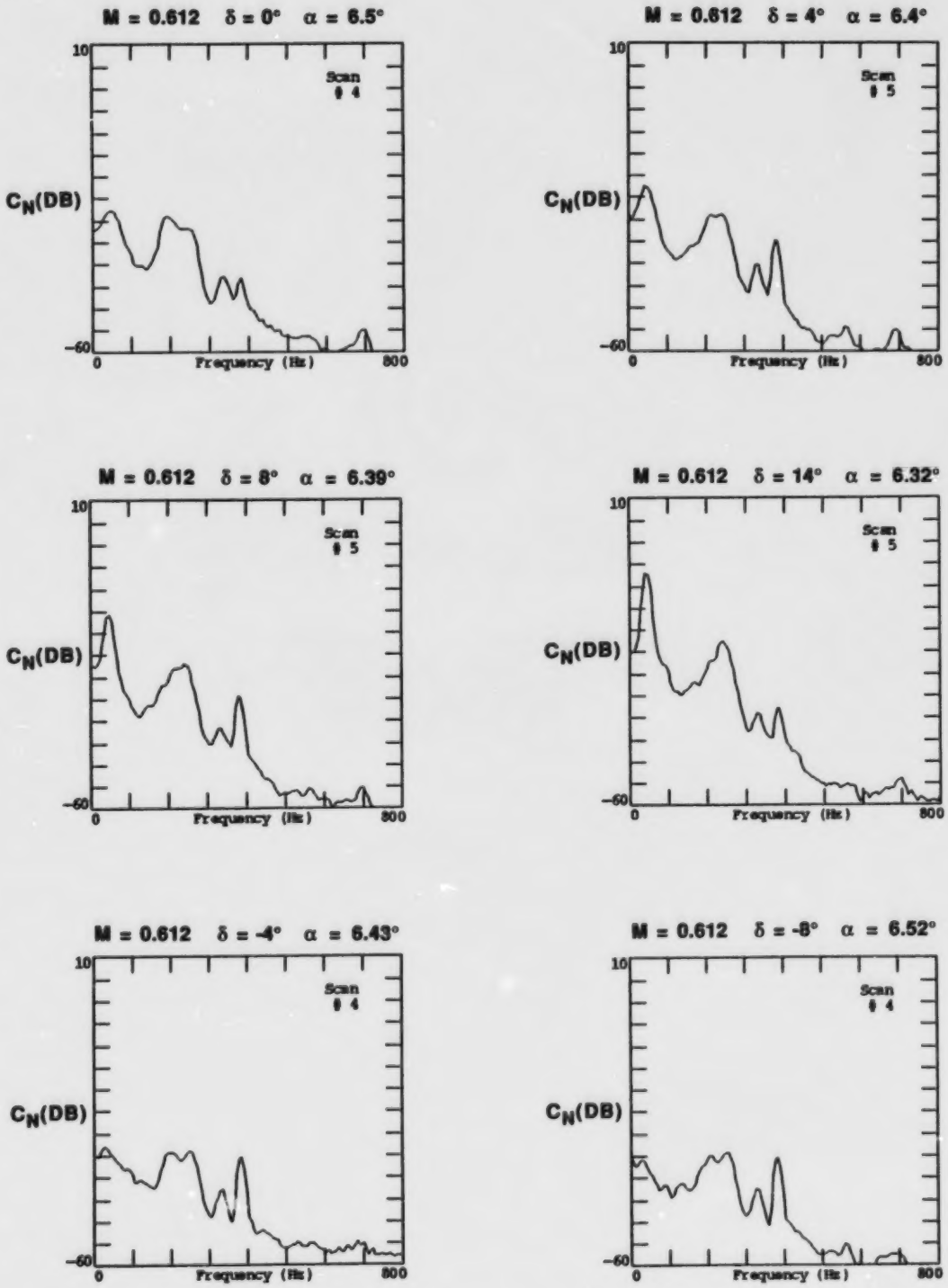

FIG. 24: POWER SPECTRA OF BALANCE NORMAL FORCE AT M ABOUT 0.612 AND α ABOUT 6.5°

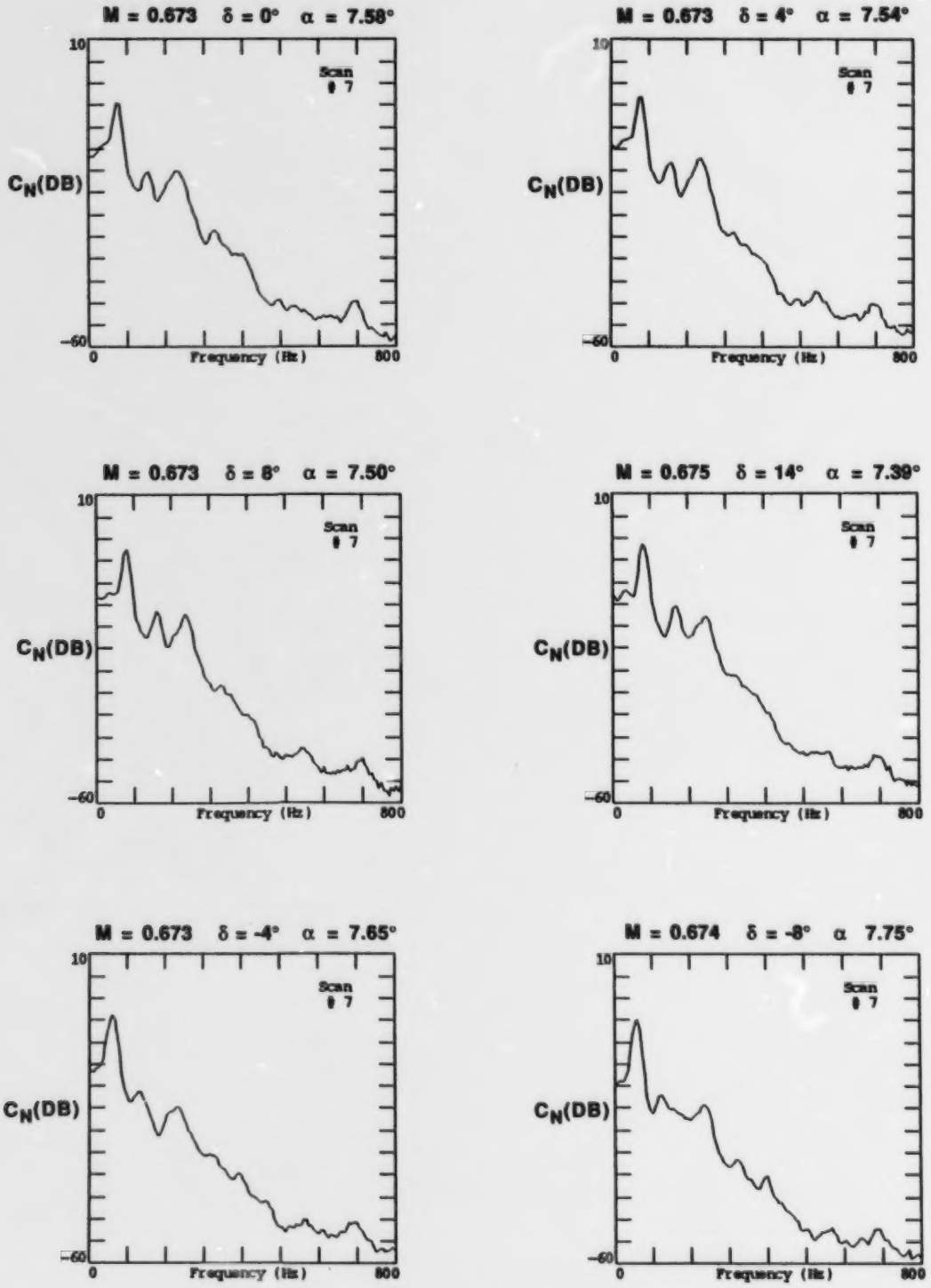

FIG. 25: POWER SPECTRA OF BALANCE NORMAL FORCE AT M ABOUT 0.673 AND α ABOUT 7.5°

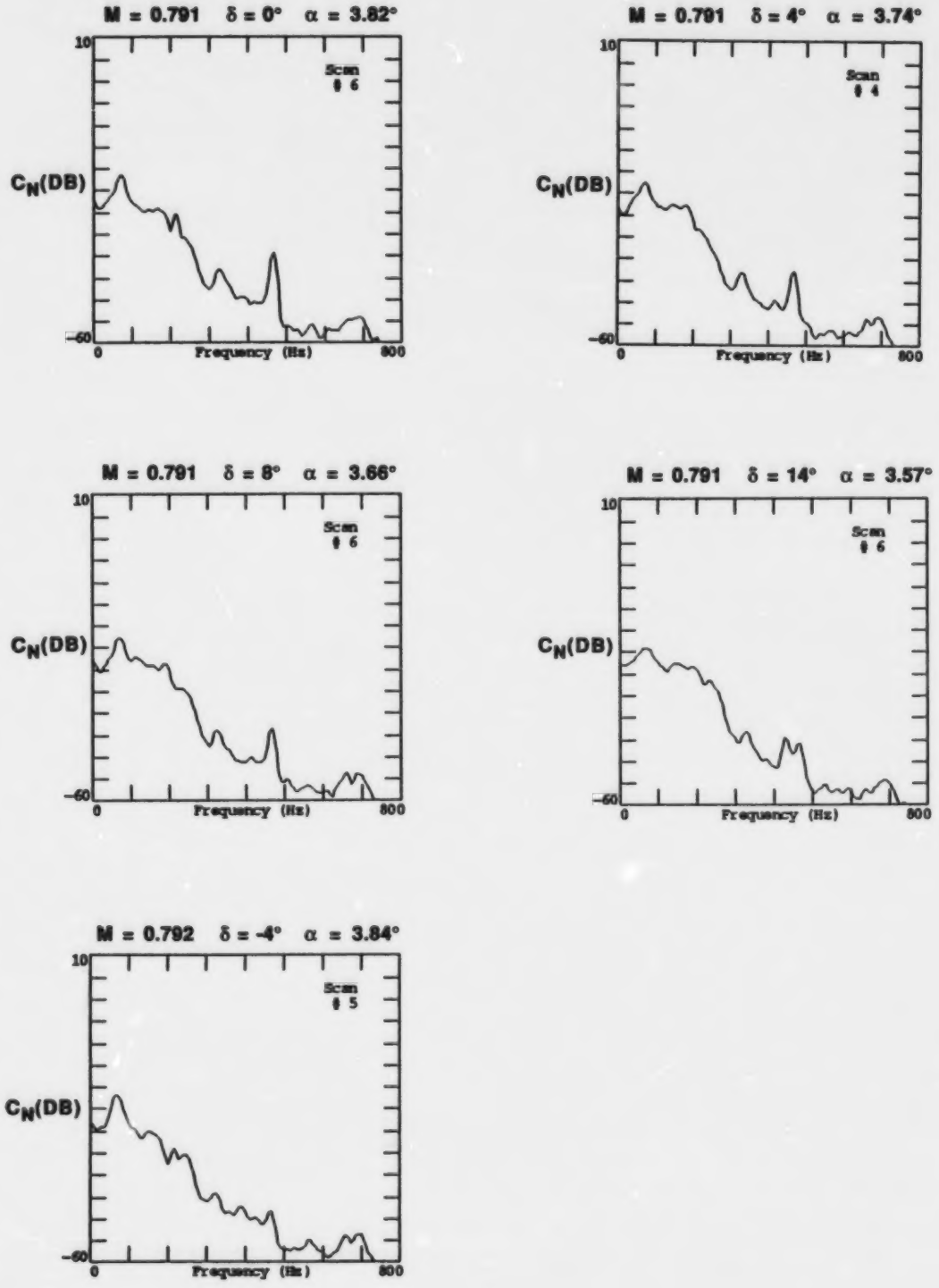

FIG. 26: POWER SPECTRA OF BALANCE NORMAL FORCE AT M ABOUT 0.791 AND α ABOUT 3.75°

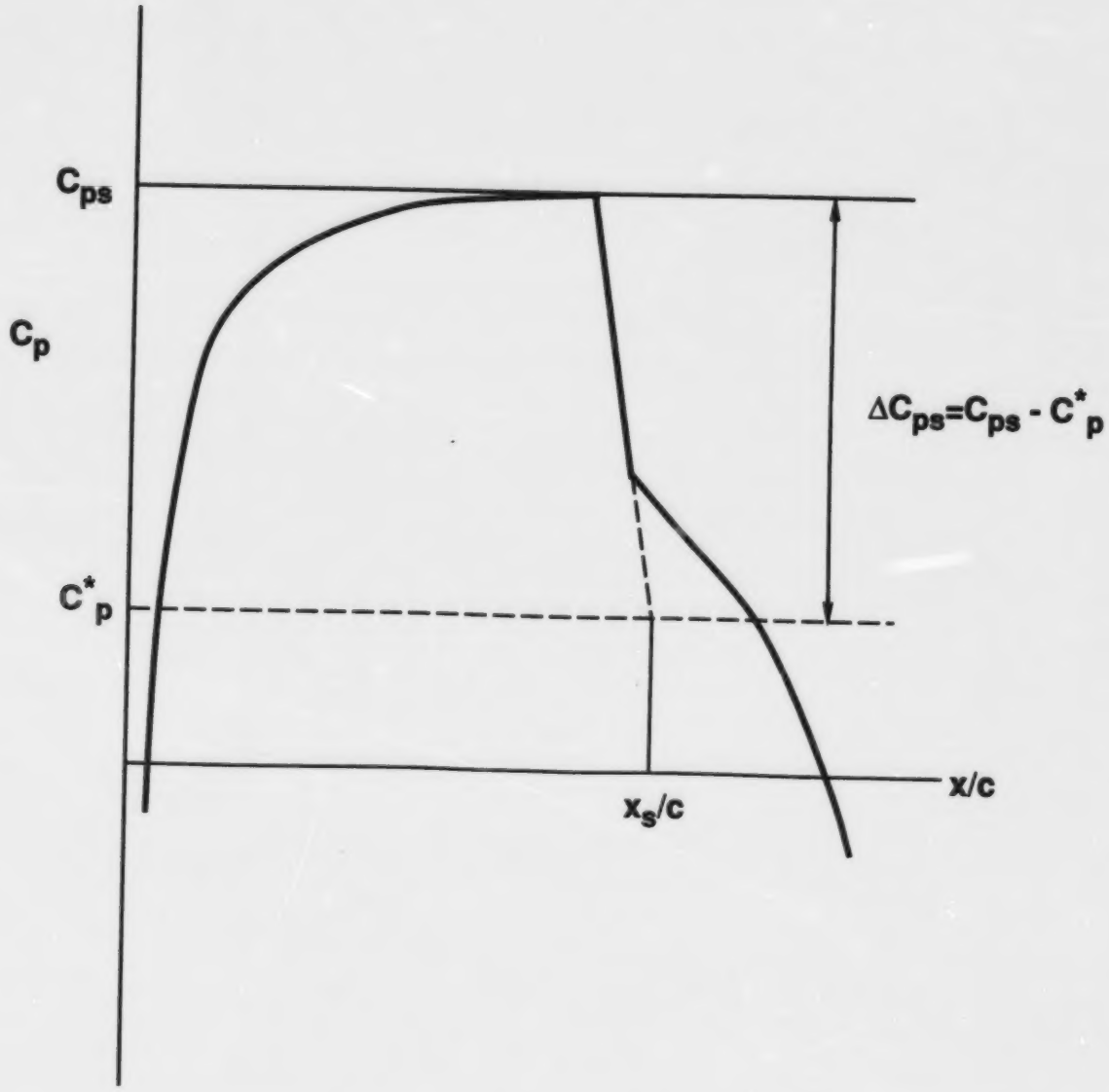

FIG. 27: DEFINITION OF SHOCK LOCATION AND STRENGTH

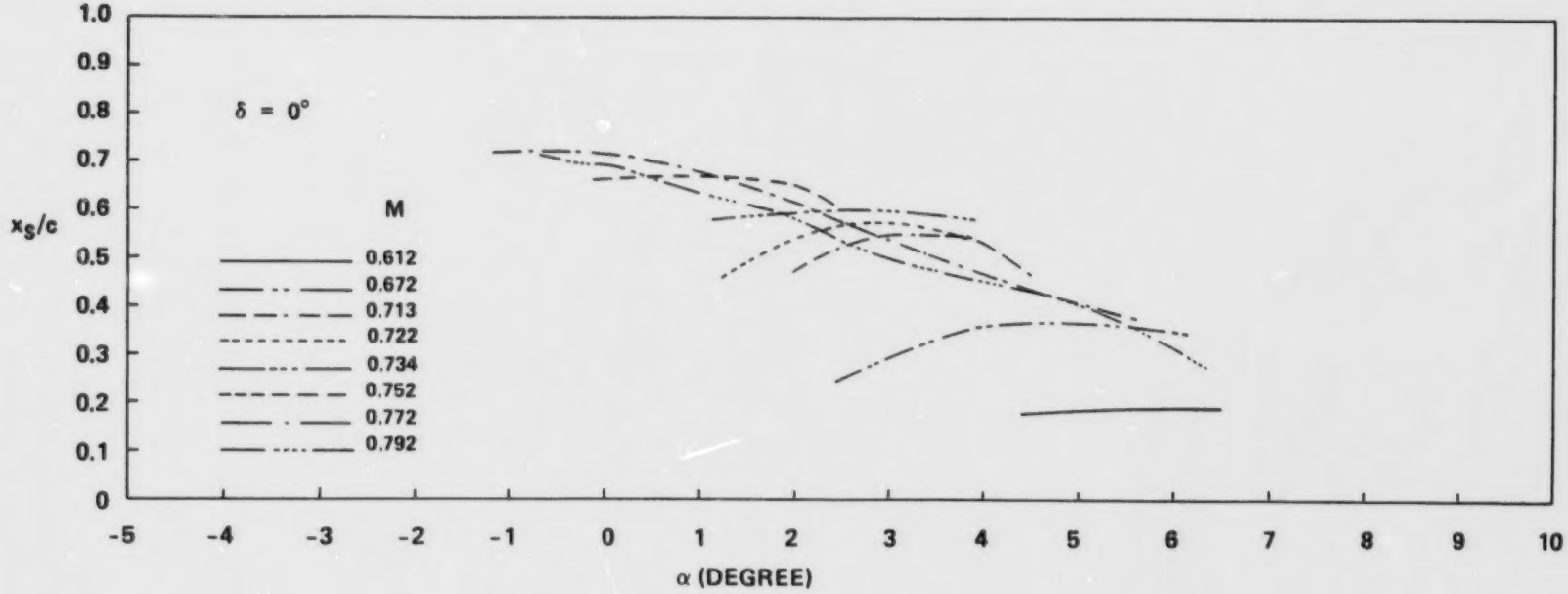

FIG. 28: SHOCK LOCATIONS VERSUS ANGLE OF INCIDENCE AT VARIOUS MACH NUMBERS FOR FLAP ANGLE δ = 0°

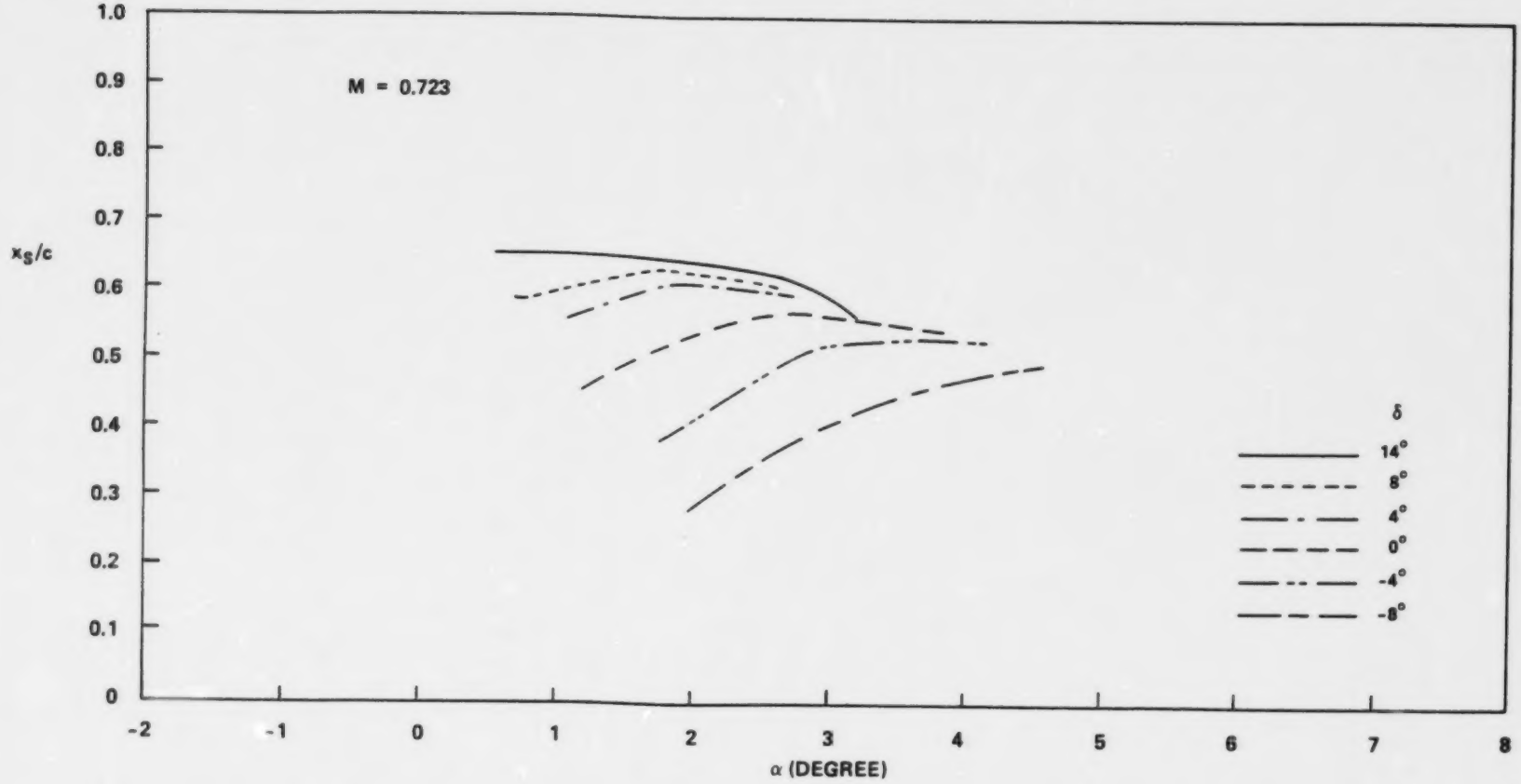

FIG. 29: SHOCK LOCATIONS VERSUS ANGLE OF INCIDENCE AT M = 0.723 FOR VARIOUS FLAP ANGLES

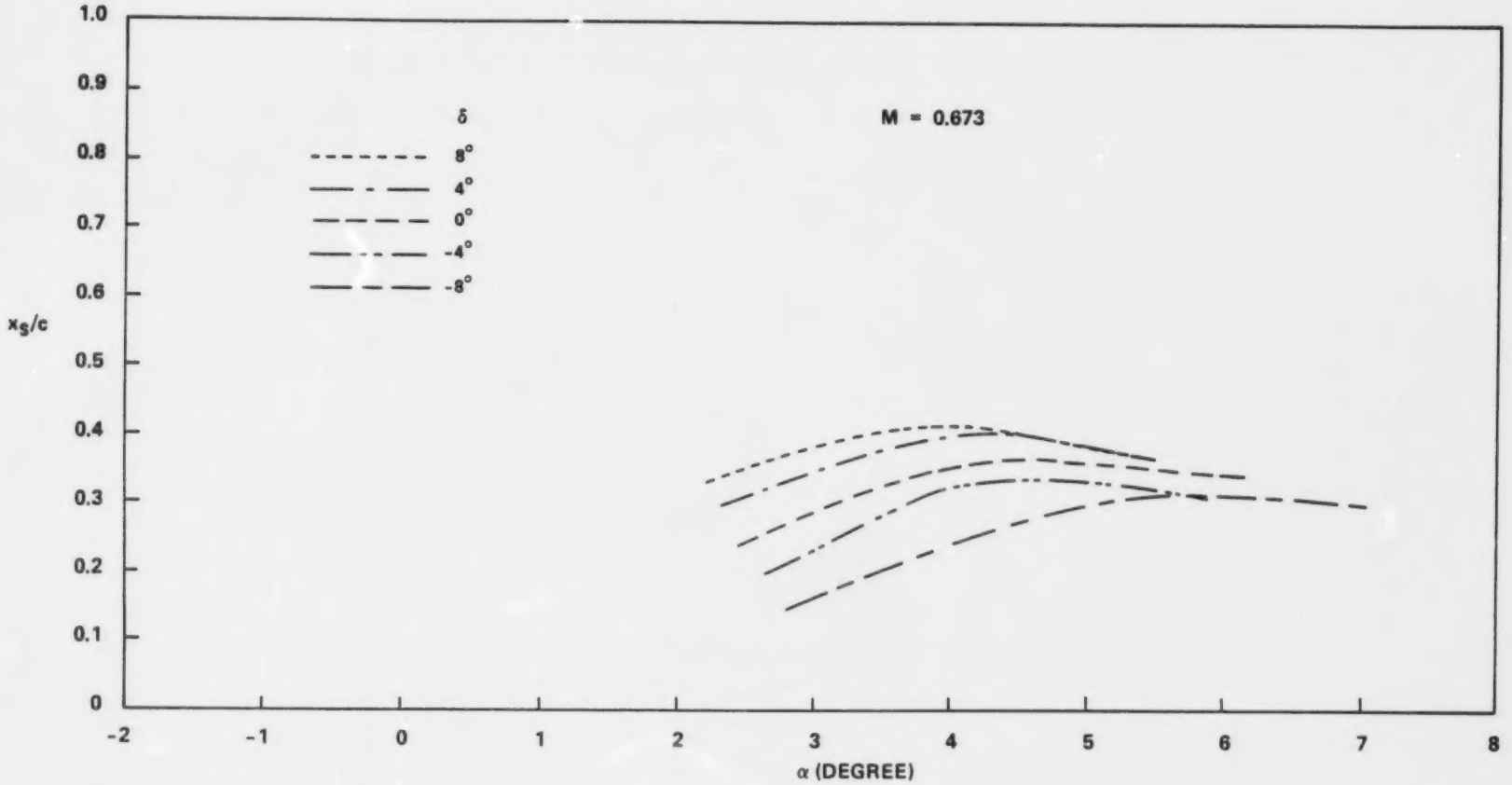

FIG. 30: SHOCK LOCATIONS VERSUS ANGLE OF INCIDENCE AT M = 0.673 FOR VARIOUS FLAP ANGLES

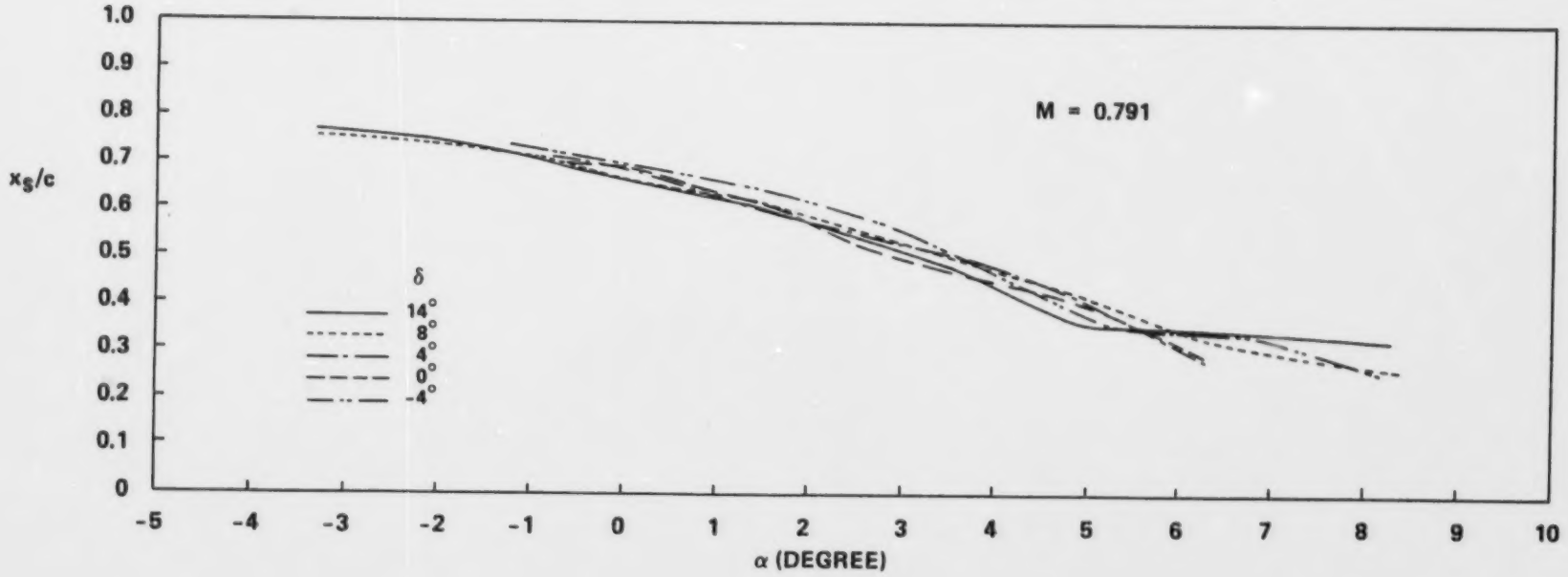

FIG. 31: SHOCK LOCATIONS VERSUS ANGLE OF INCIDENCE AT M = 0.791 FOR VARIOUS FLAP ANGLES

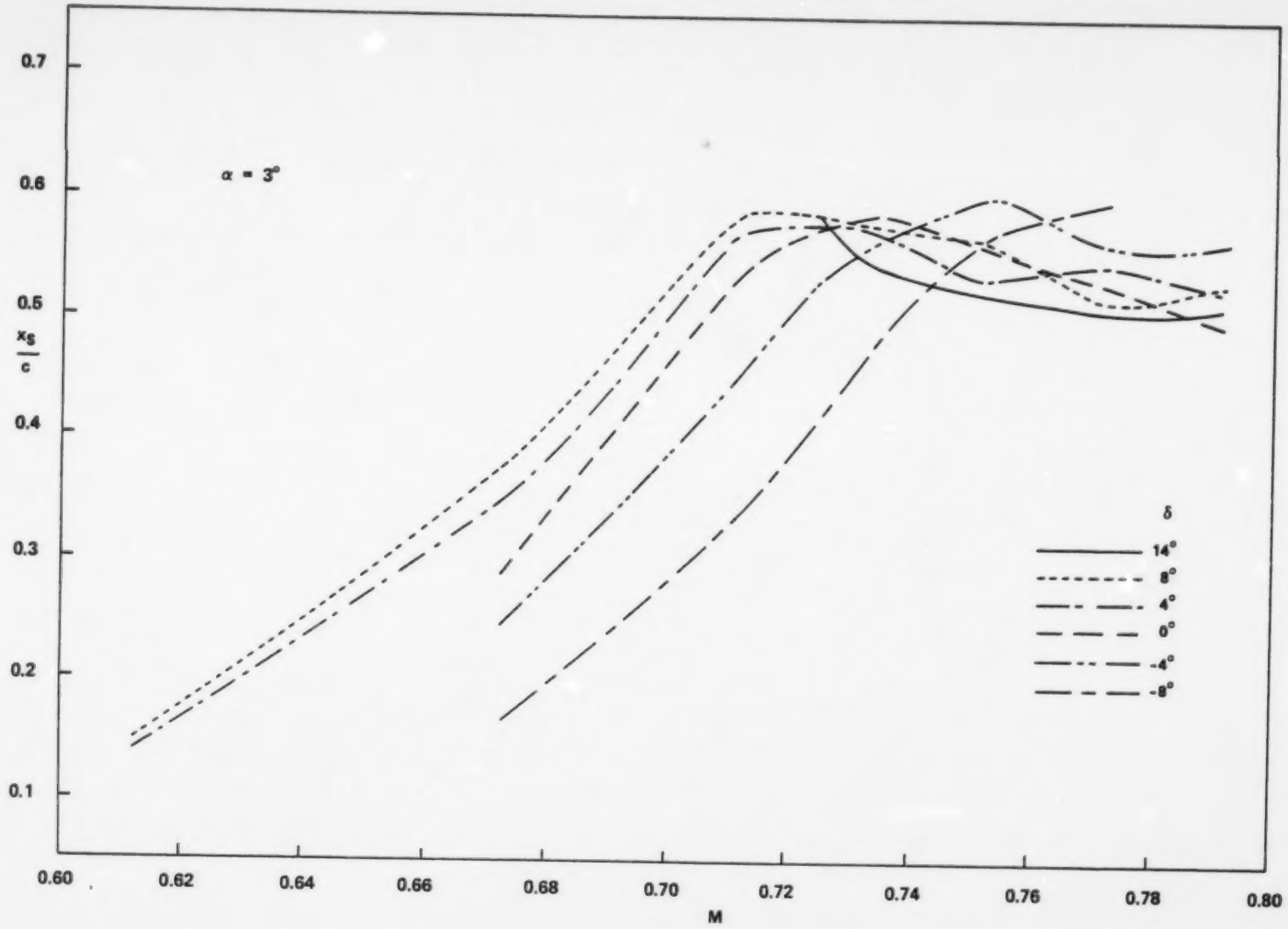

FIG. 32: SHOCK LOCATIONS VERSUS MACH NUMBER AT ANGLE OF INCIDENCE α = 3° FOR VARIOUS FLAP ANGLES

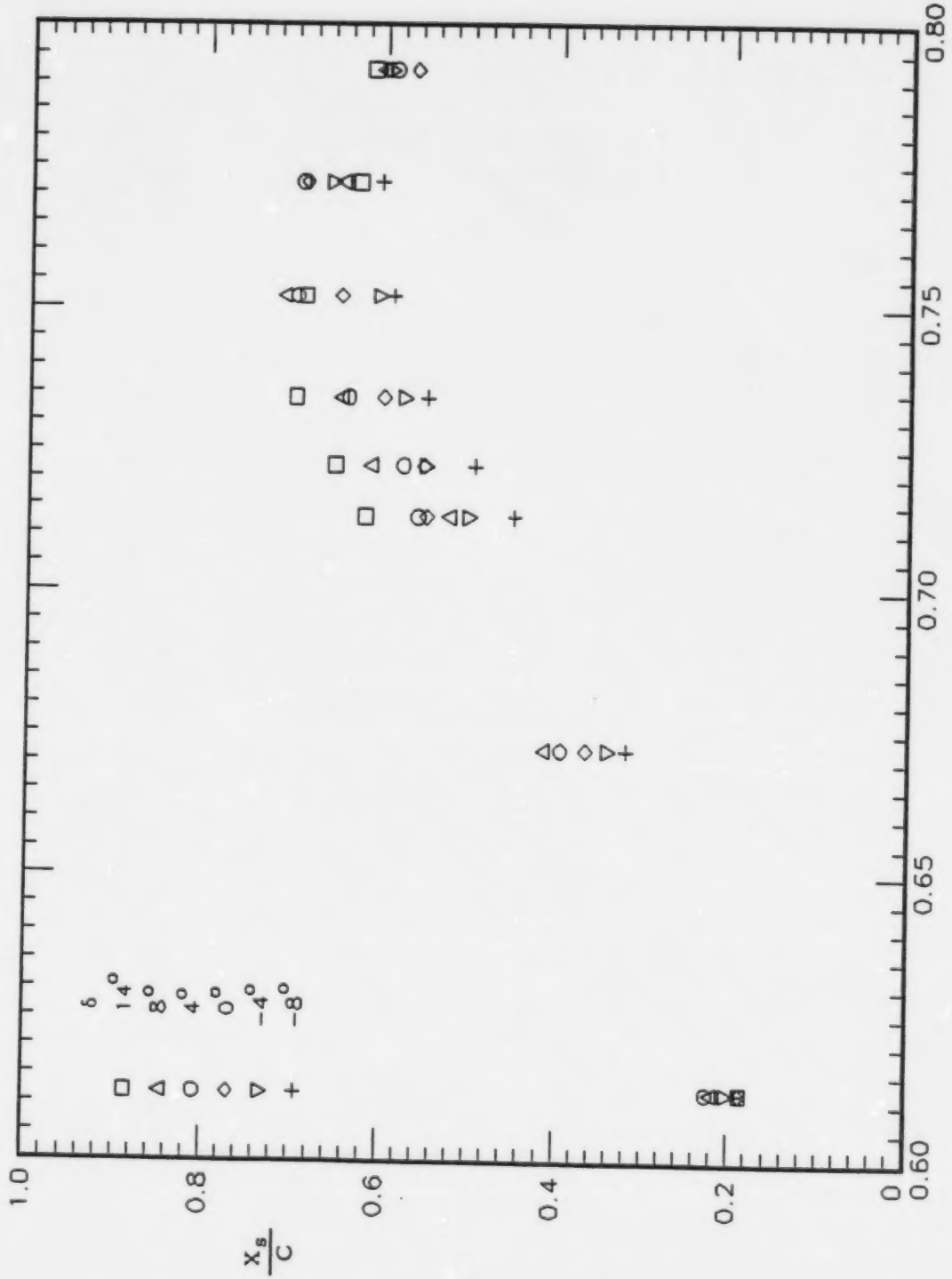

FIG. 33: SHOCK LOCATIONS VERSUS MACH NUMBER AT BUFFET ONSET FOR VARIOUS FLAP ANGLES

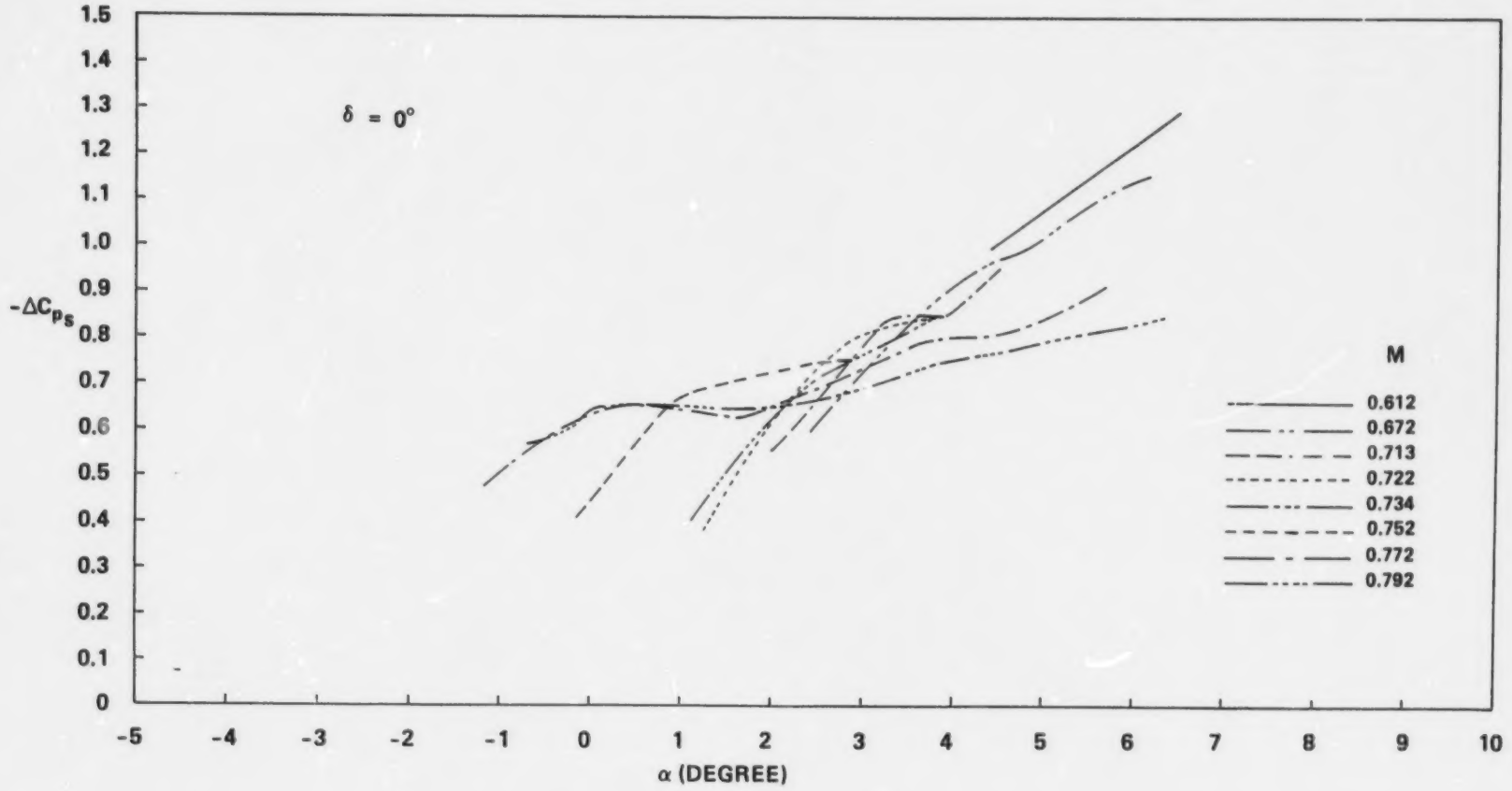

FIG. 34: SHOCK STRENGTHS VERSUS ANGLE OF INCIDENCE AT VARIOUS MACH NUMBERS FOR FLAP ANGLE δ = 0°

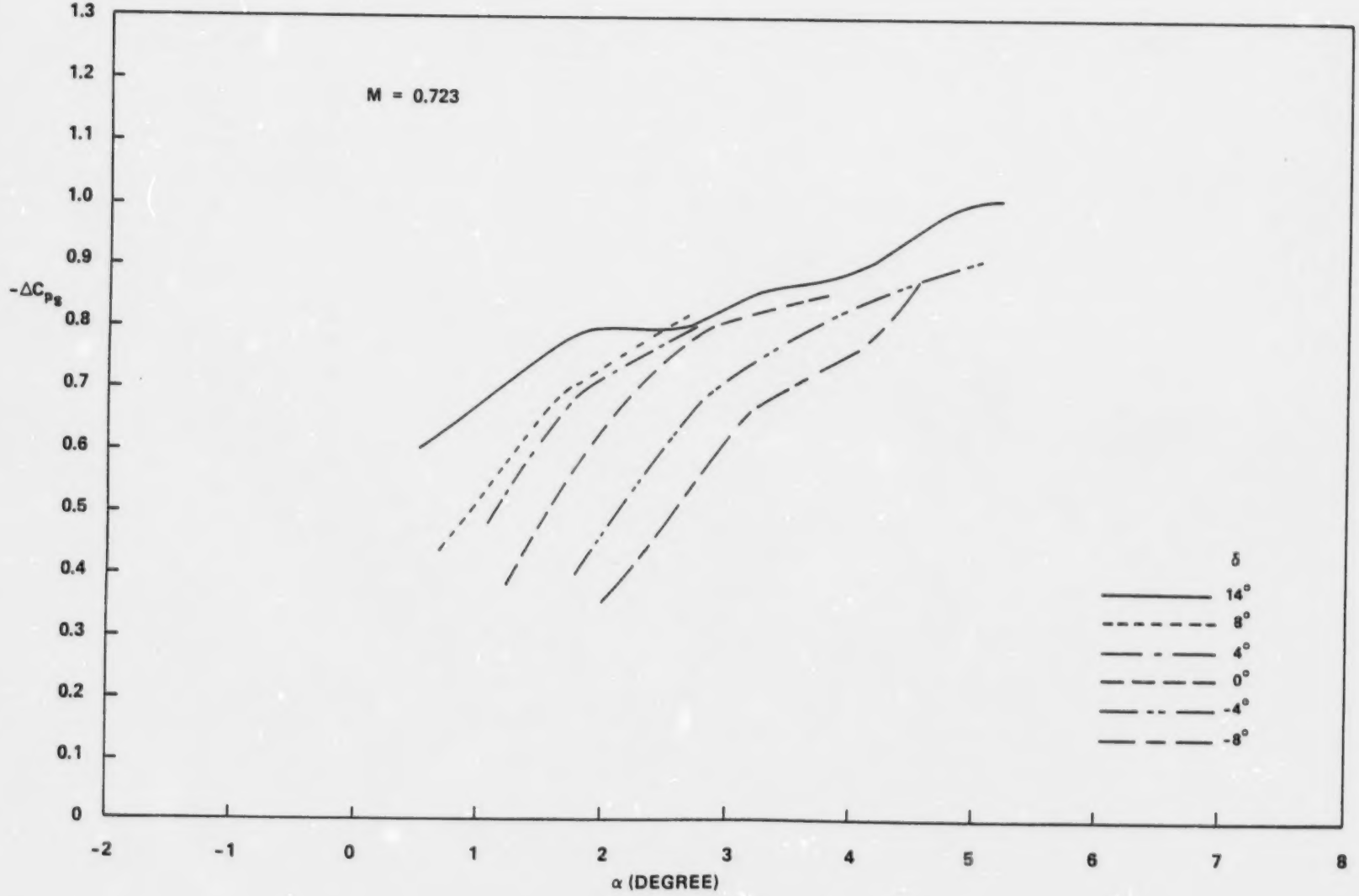

FIG. 35: SHOCK STRENGTHS VERSUS ANGLE OF INCIDENCE AT M = 0.723 FOR VARIOUS FLAP ANGLES

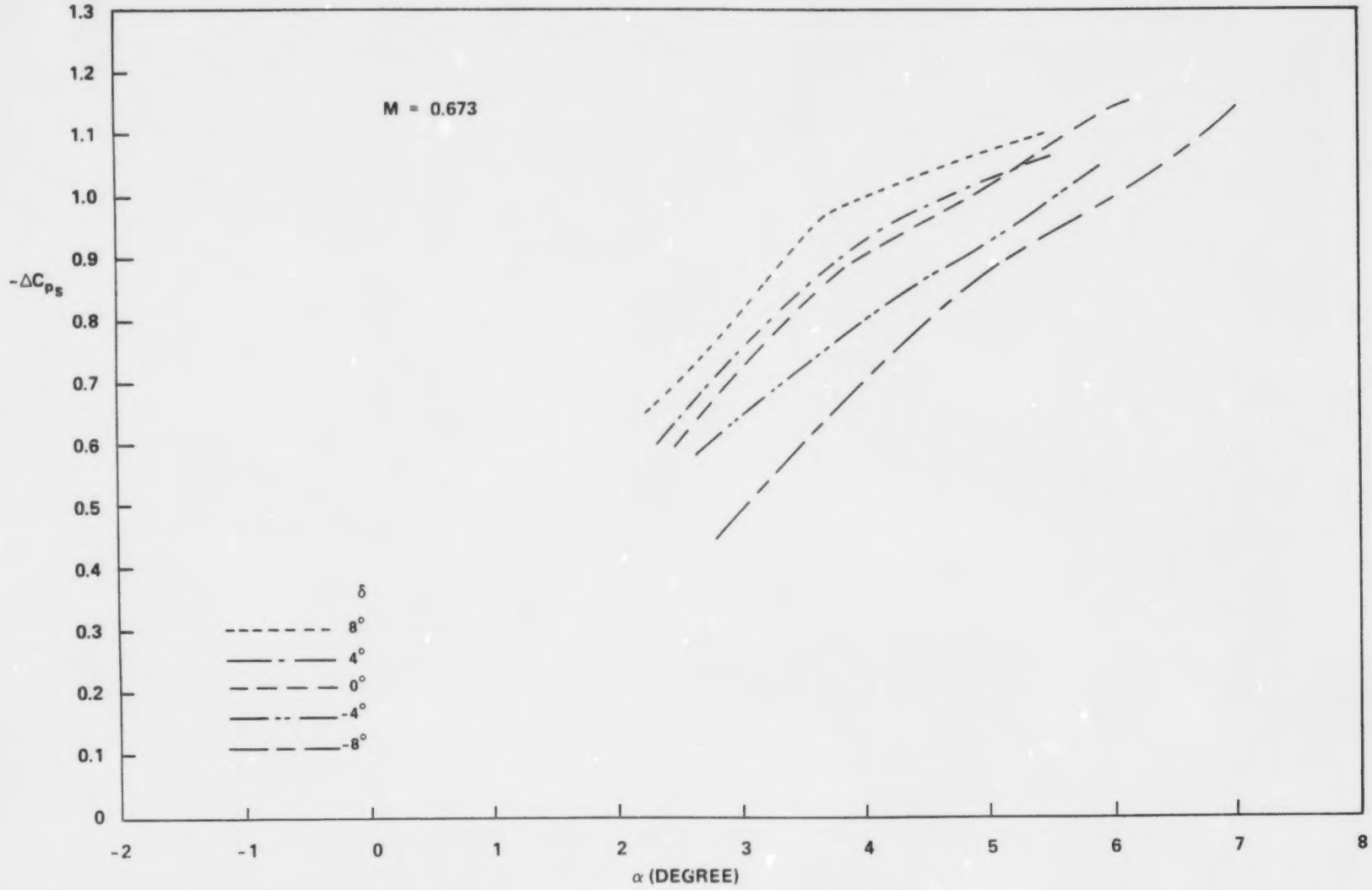

FIG. 36: SHOCK STRENGTHS VERSUS ANGLE OF INCIDENCE AT M = 0.673 FOR VARIOUS FLAP ANGLES

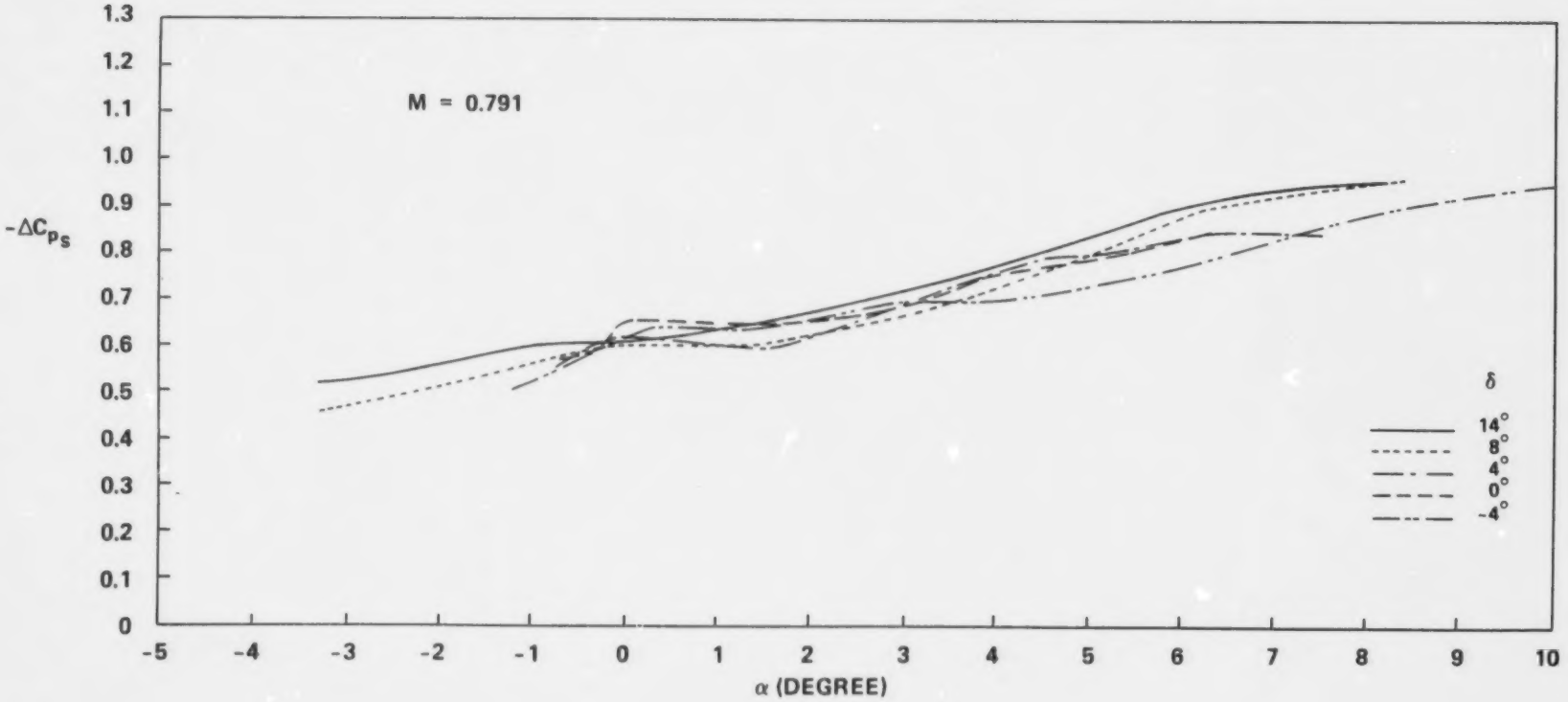

FIG. 37: SHOCK STRENGTHS VERSUS ANGLE OF INCIDENCE AT M = 0.791 FOR VARIOUS FLAP ANGLES

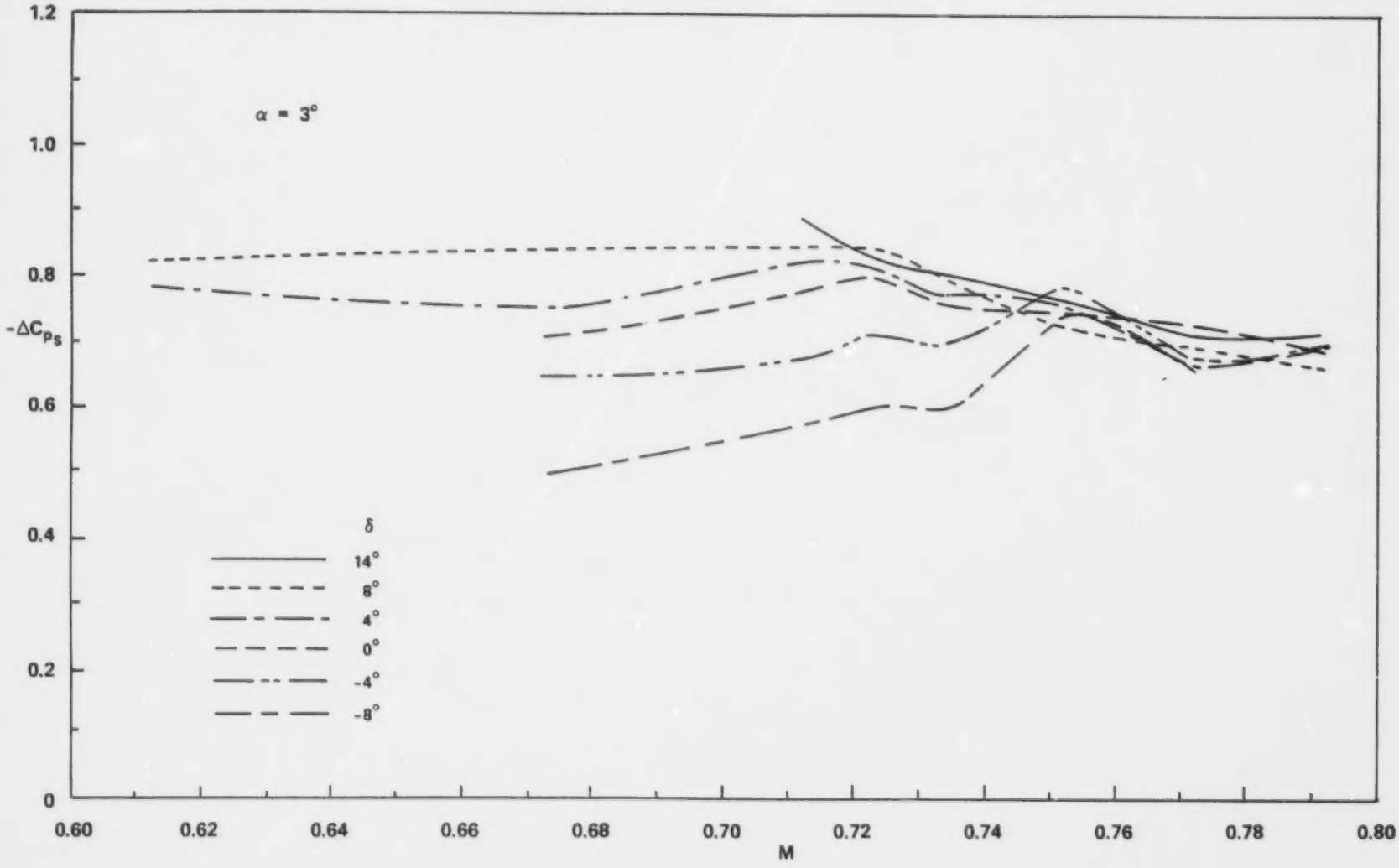

FIG. 38: SHOCK STRENGTHS VERSUS MACH NUMBER AT ANGLE OF INCIDENCE α = 3° FOR VARIOUS FLAP ANGLES

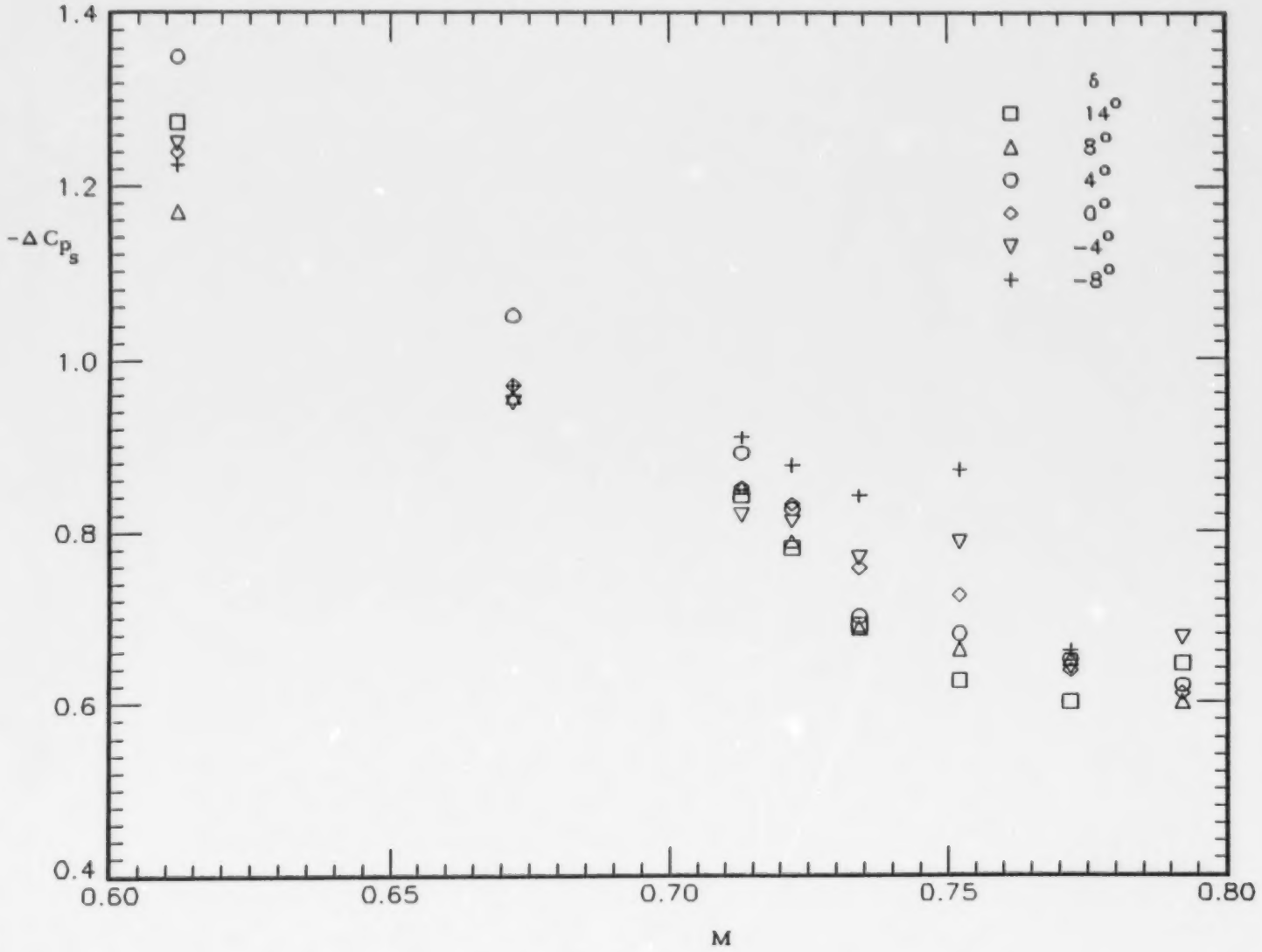

FIG. 39: SHOCK STRENGTHS VERSUS MACH NUMBER AT BUFFET ONSET FOR VARIOUS FLAP ANGLES

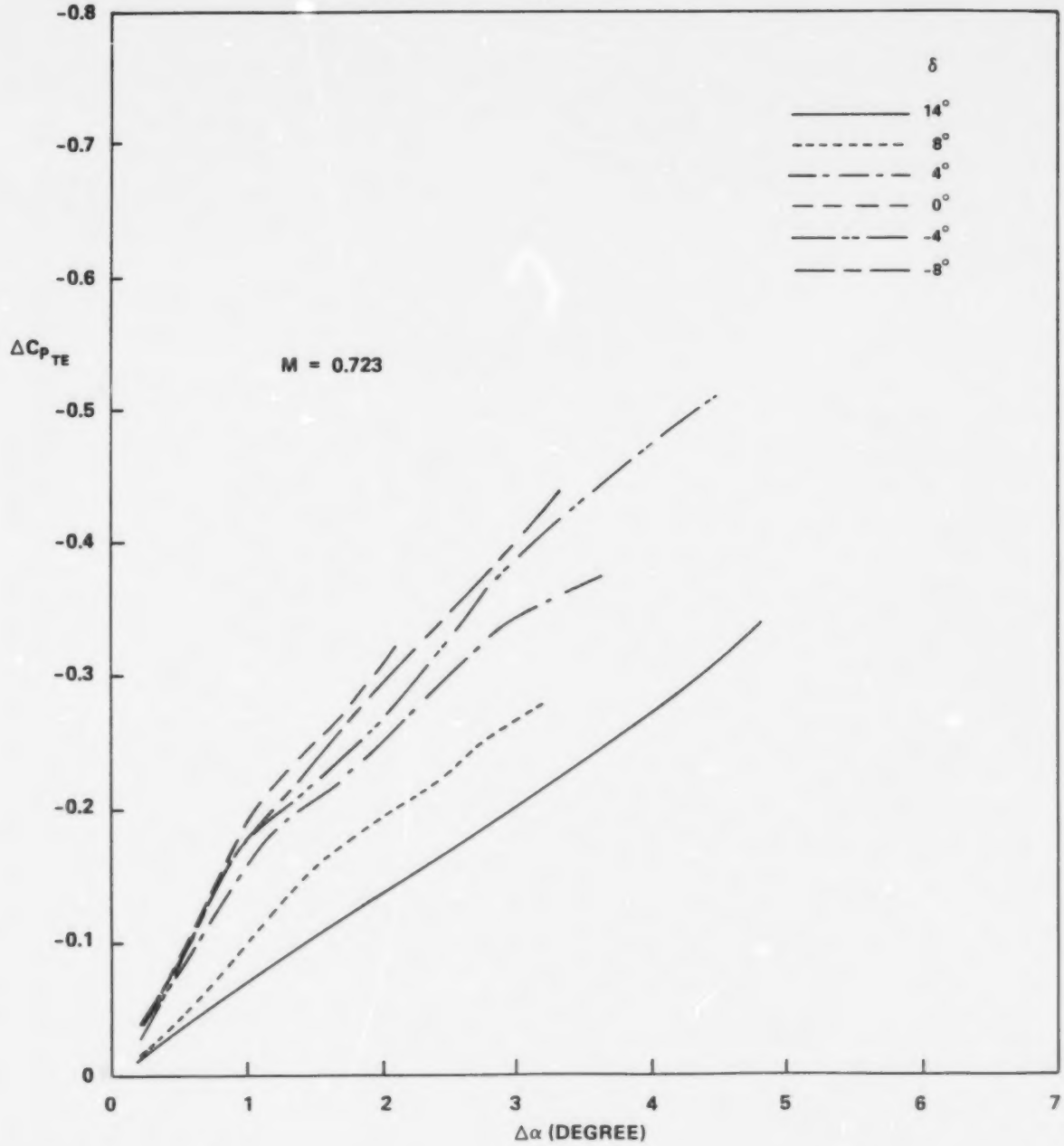

FIG. 40: $\Delta C_{P_{TE}}$ VERSUS $\Delta\alpha$ AT M = 0.723 FOR VARIOUS FLAP ANGLES

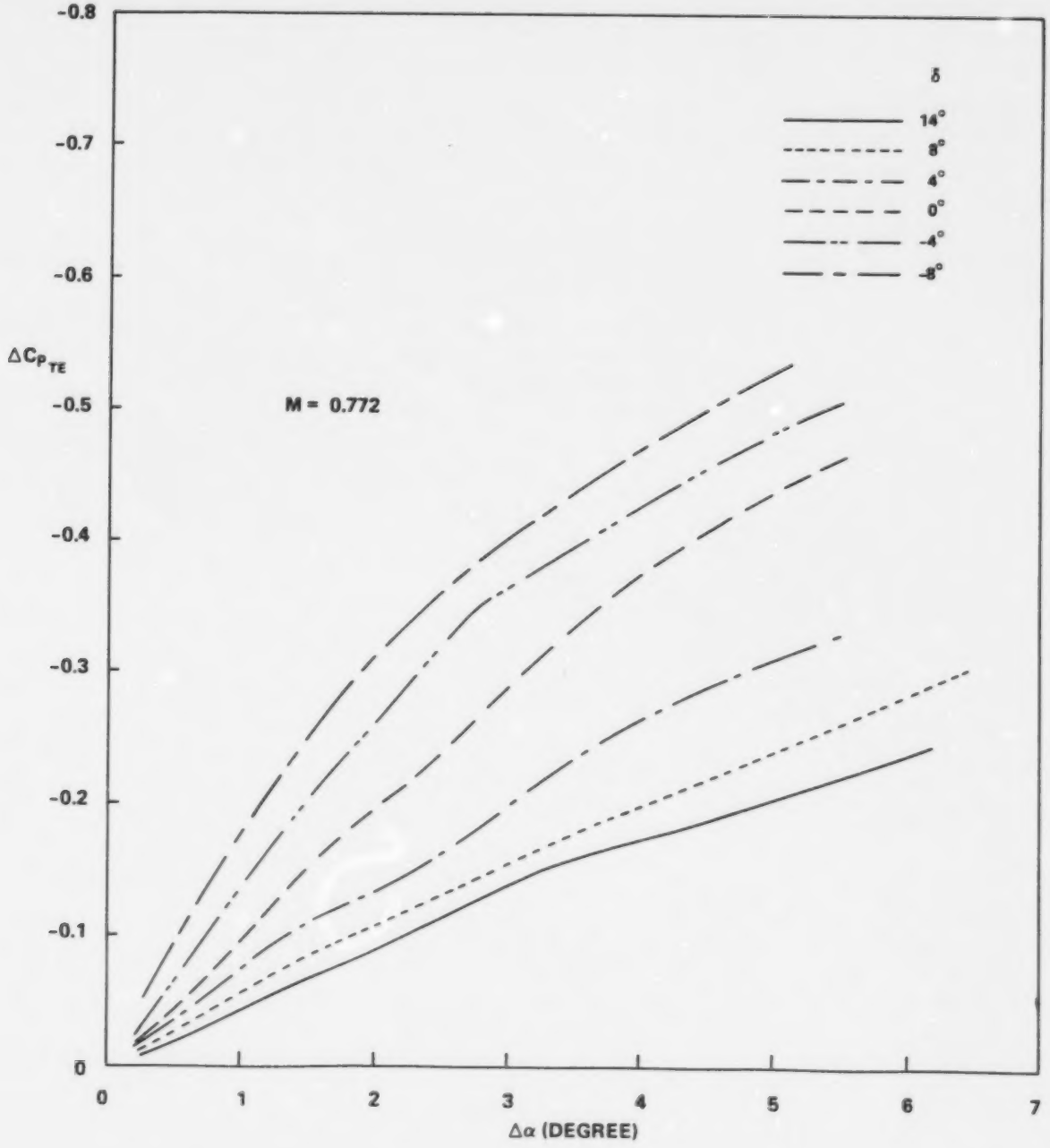

FIG. 41: $\Delta C_{P_{TE}}$ VERSUS $\Delta\alpha$ AT M = 0.772 FOR VARIOUS FLAP ANGLES

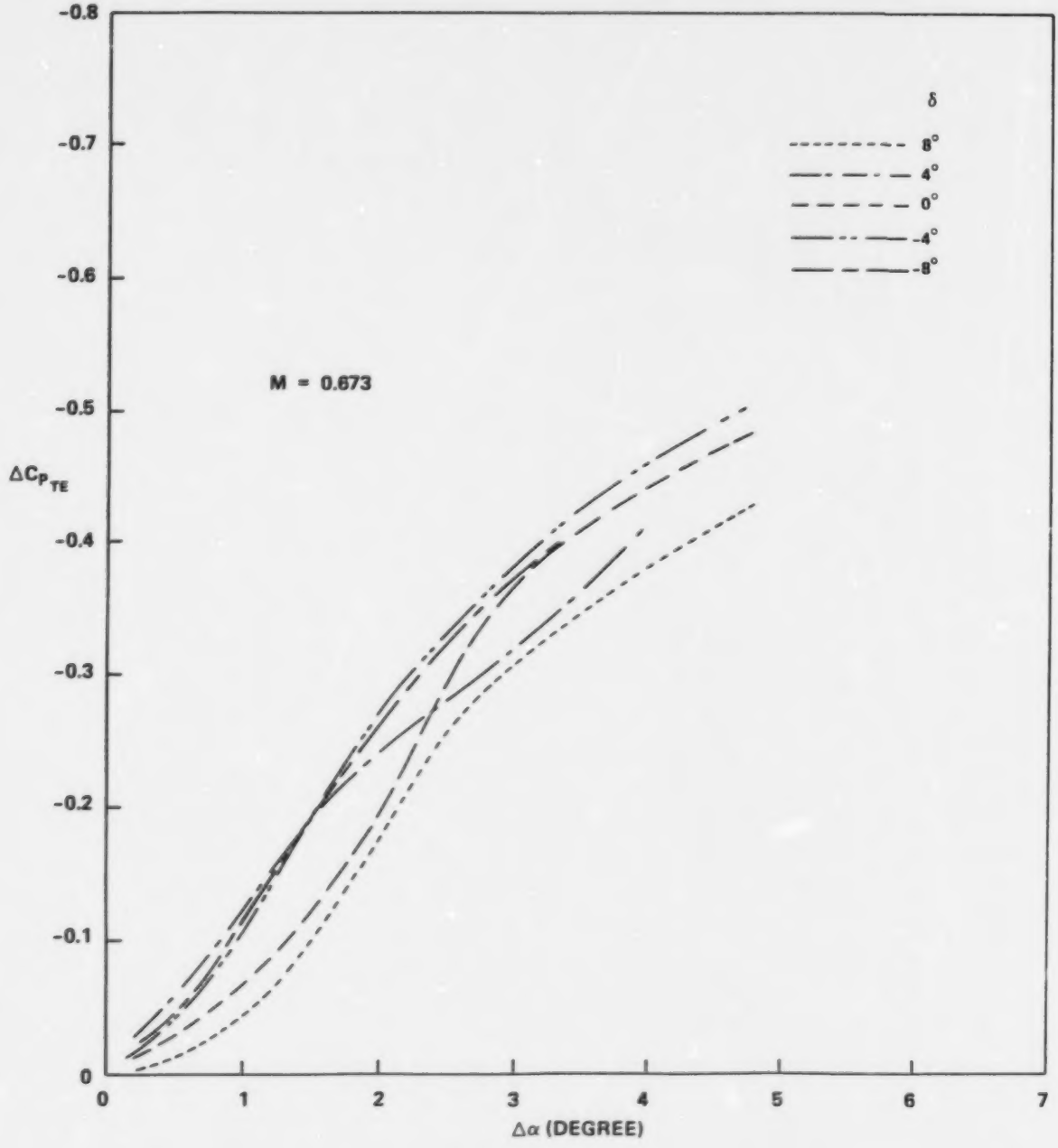

FIG. 42: $\Delta C_{P_{TE}}$ VERSUS $\Delta\alpha$ AT M = 0.673 FOR VARIOUS FLAP ANGLES

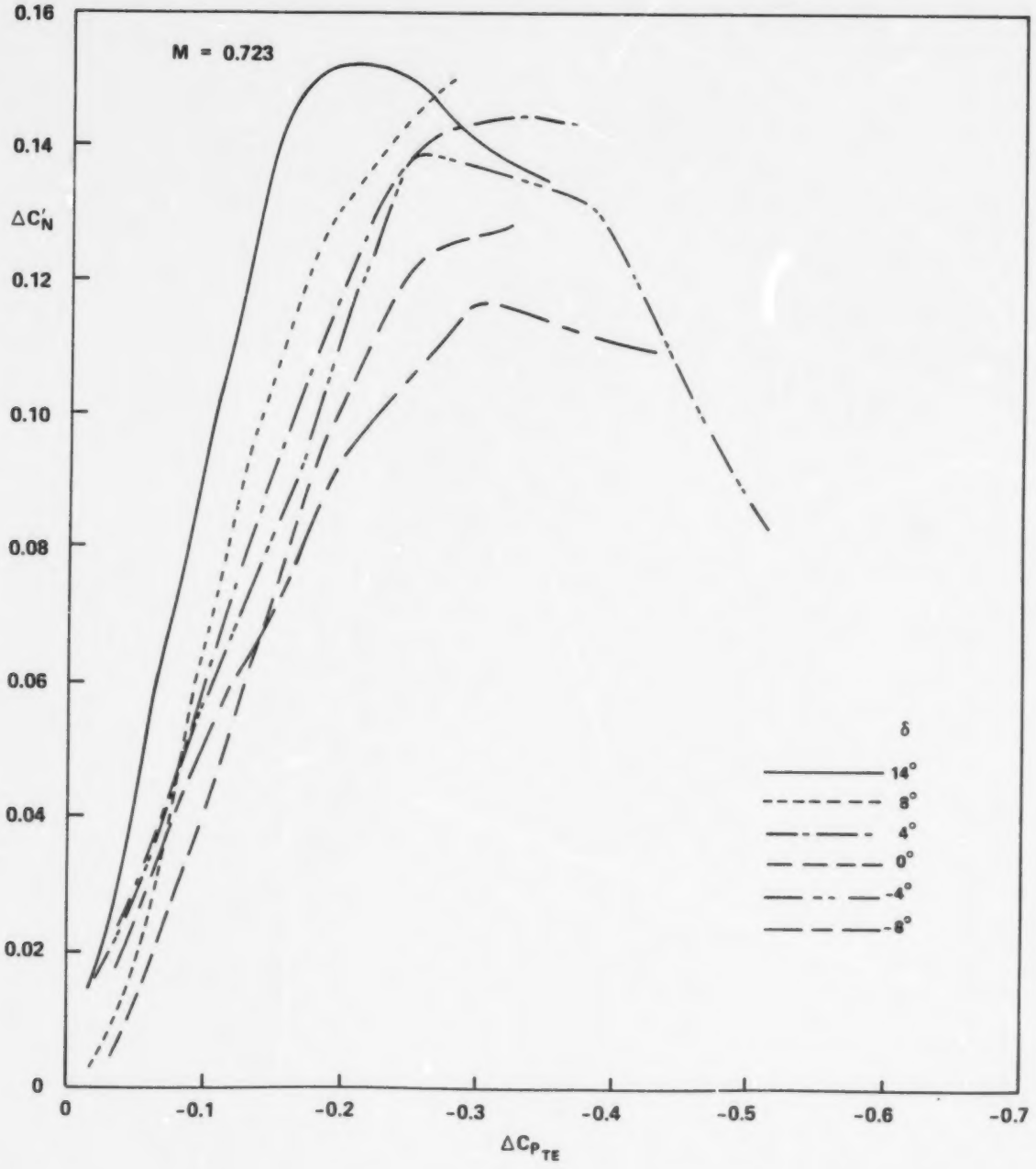

FIG. 43: $\Delta C'_N$ VERSUS $\Delta C_{P_{TE}}$ AT M = 0.723 FOR VARIOUS FLAP ANGLES

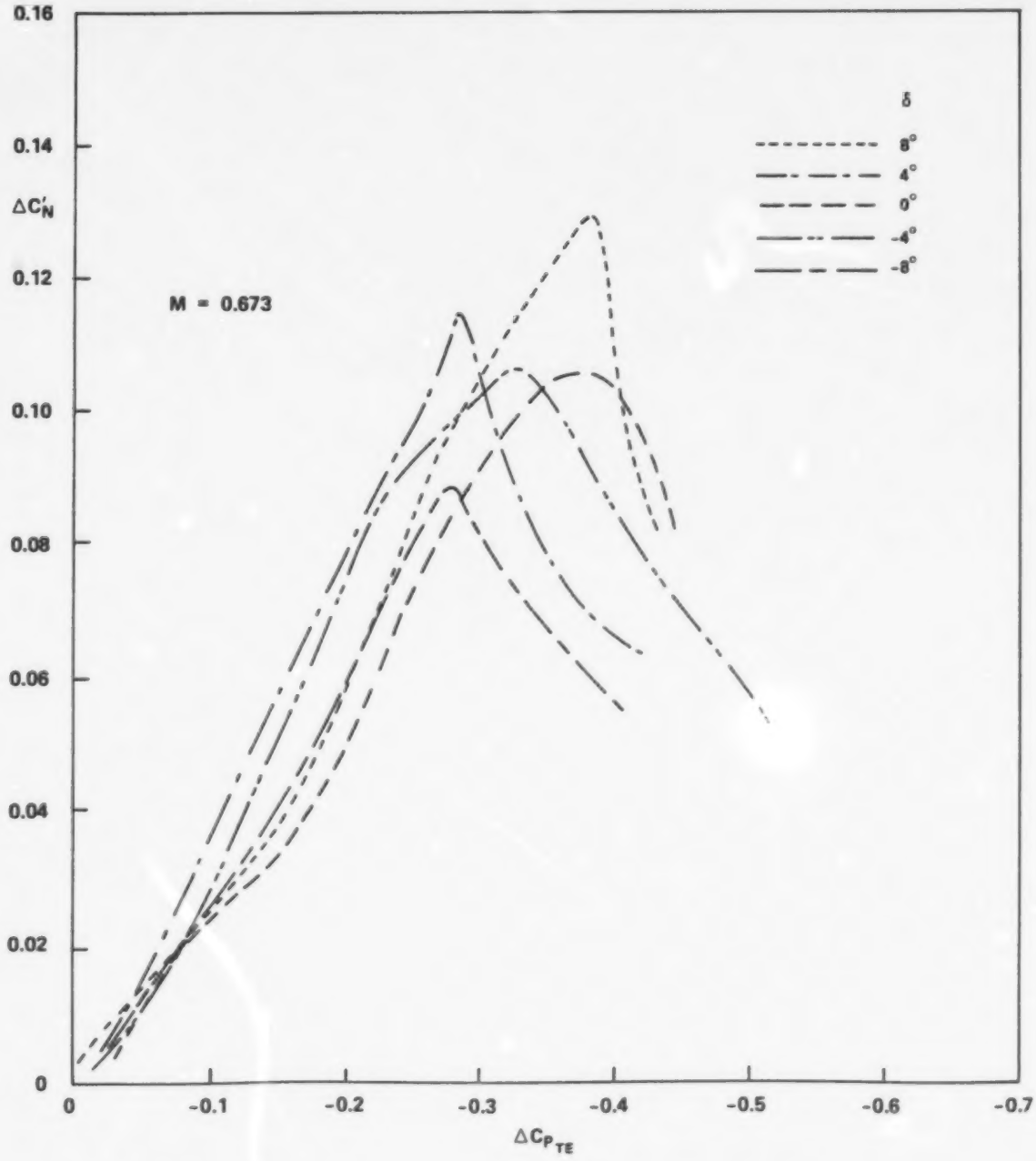

FIG. 44: $\Delta C'_N$ VERSUS $\Delta C_{P_{TE}}$ AT M = 0.673 FOR VARIOUS FLAP ANGLES

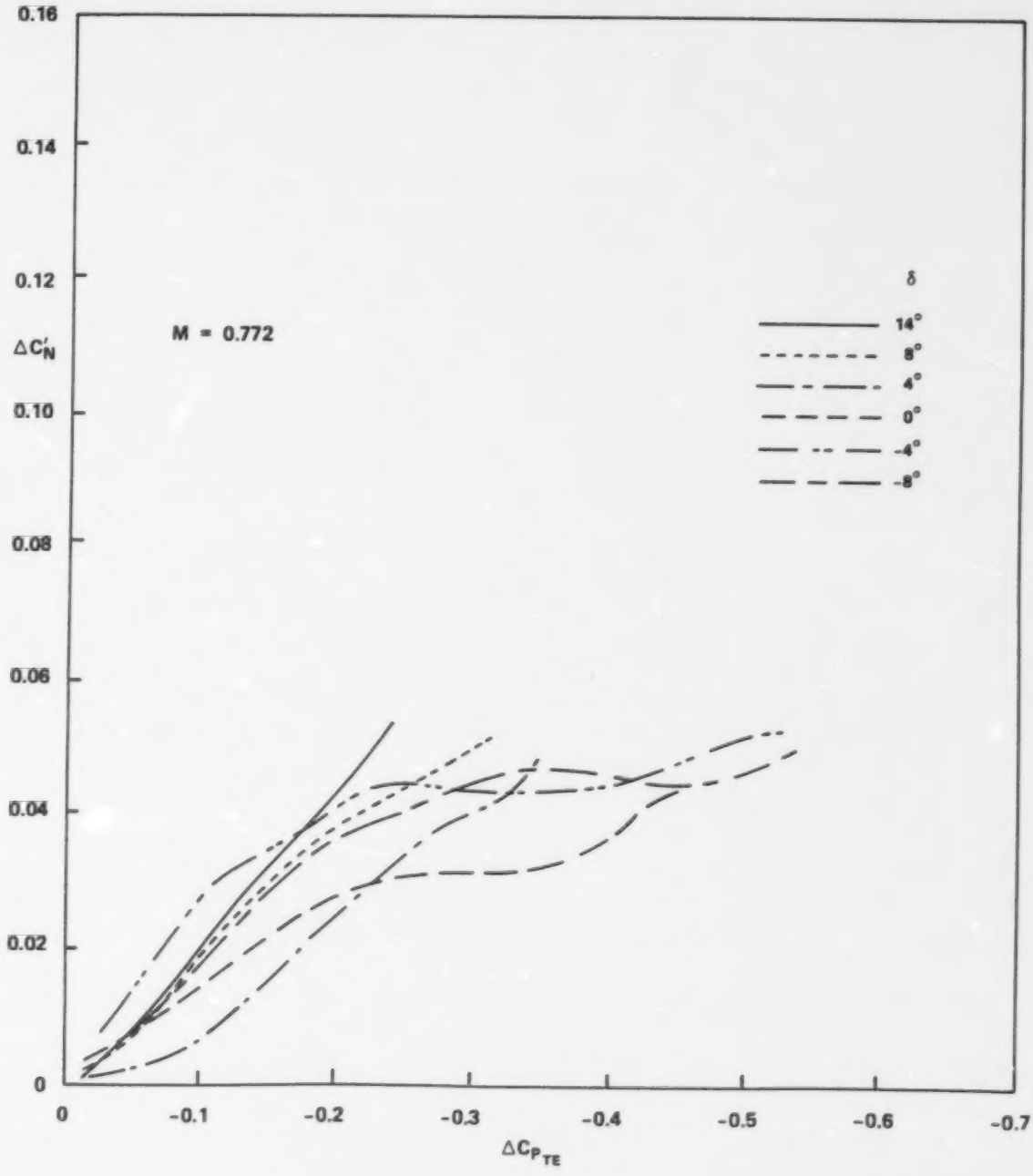

FIG. 45: $\Delta C'_N$ VERSUS $\Delta C_{P_{TE}}$ AT M = 0.772 FOR VARIOUS FLAP ANGLES

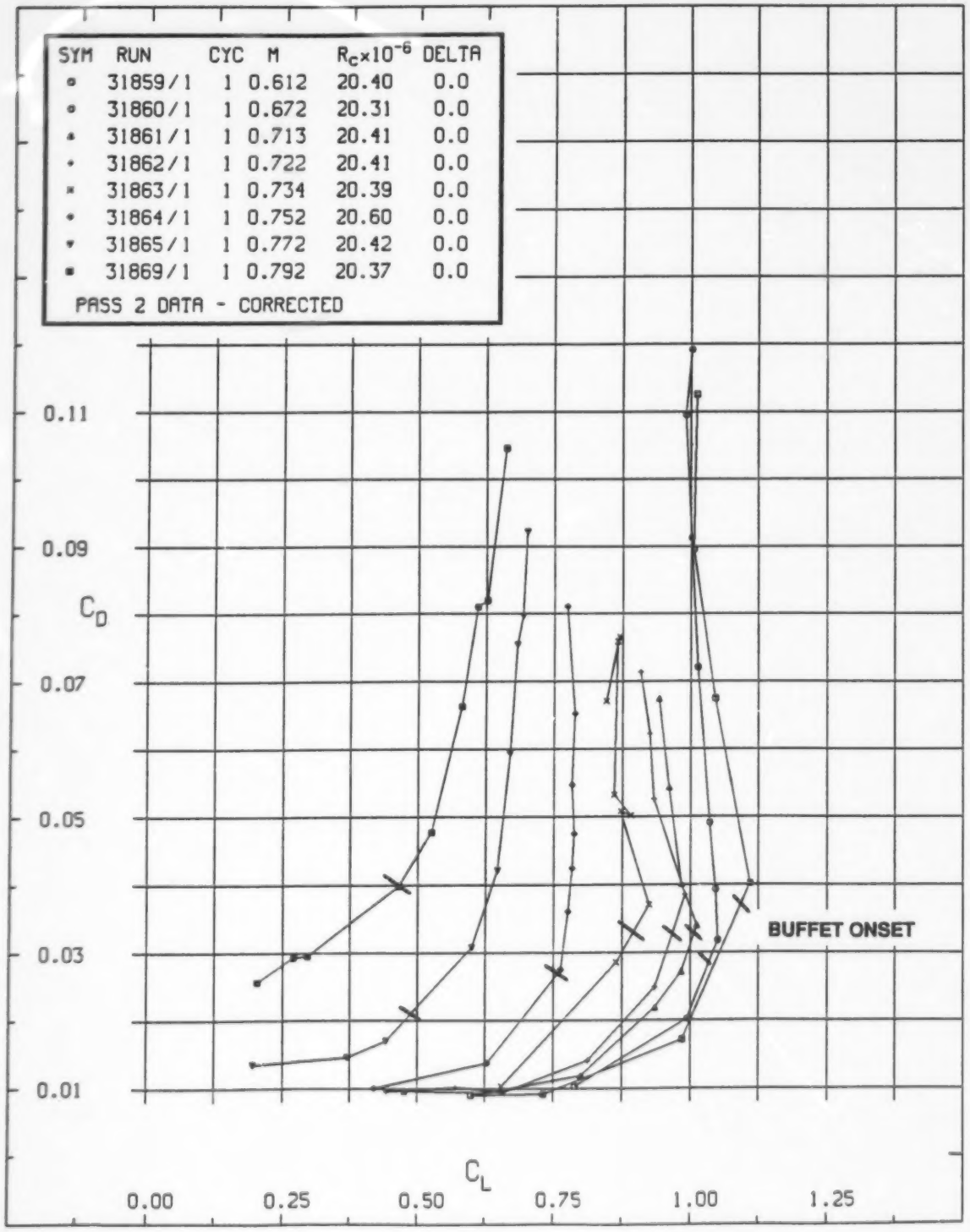

FIG. 46: DRAG VERSUS LIFT AT VARIOUS MACH NUMBERS FOR FLAP ANGLE $\delta = 0°$

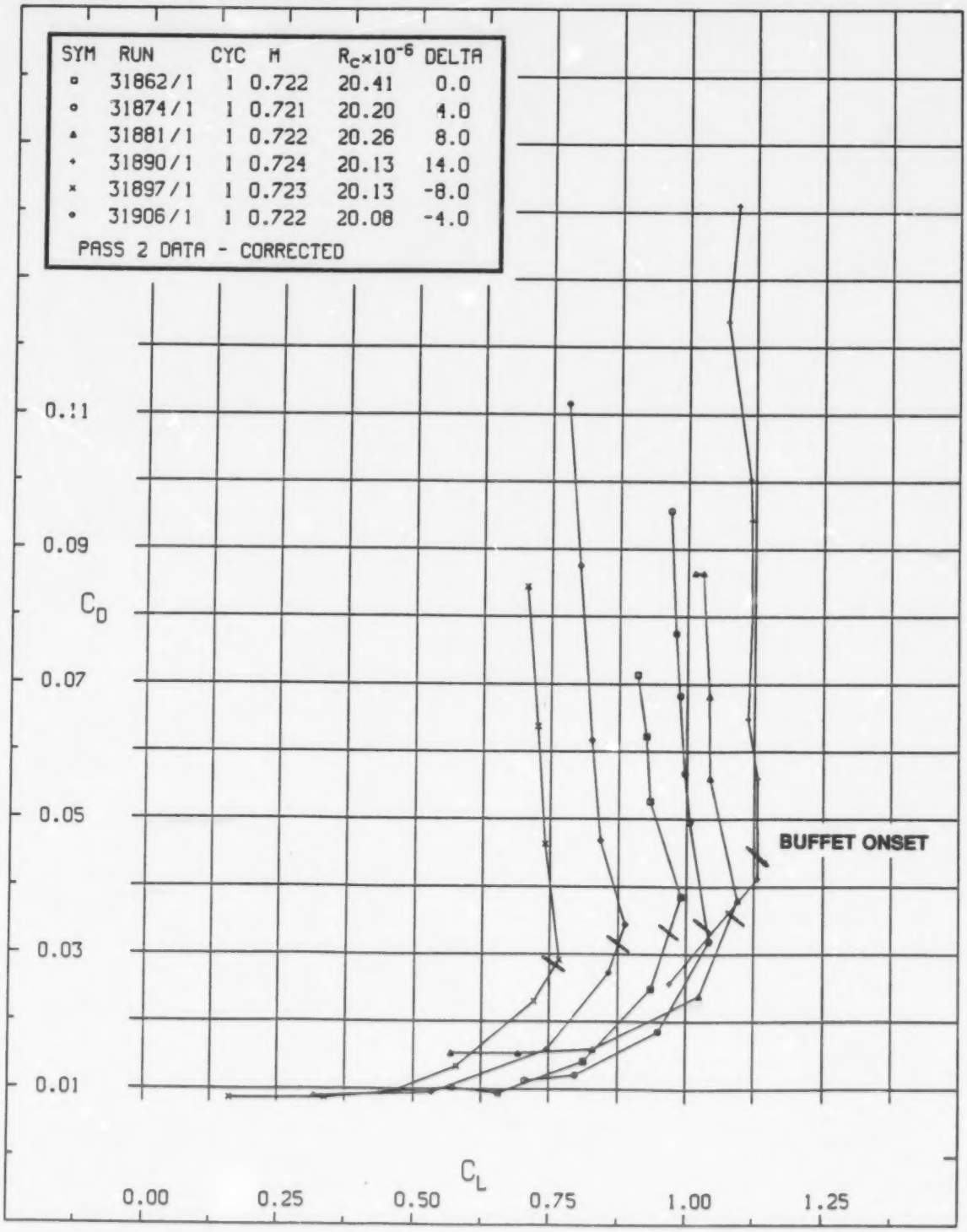

FIG. 47: DRAG VERSUS LIFT AT M ABOUT 0.723 FOR VARIOUS FLAP ANGLES

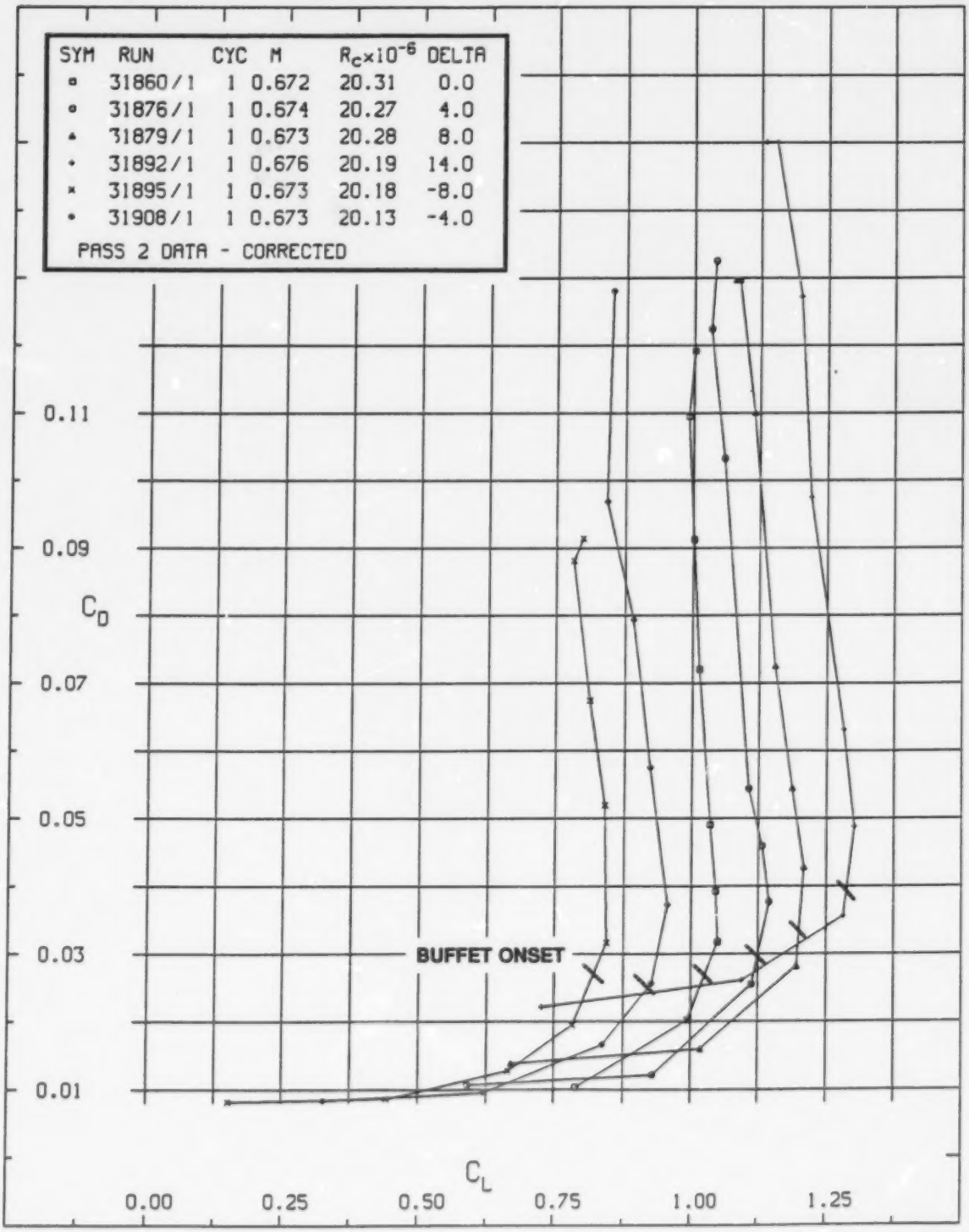

FIG. 48: DRAG VERSUS LIFT AT M ABOUT 0.673 FOR VARIOUS FLAP ANGLES

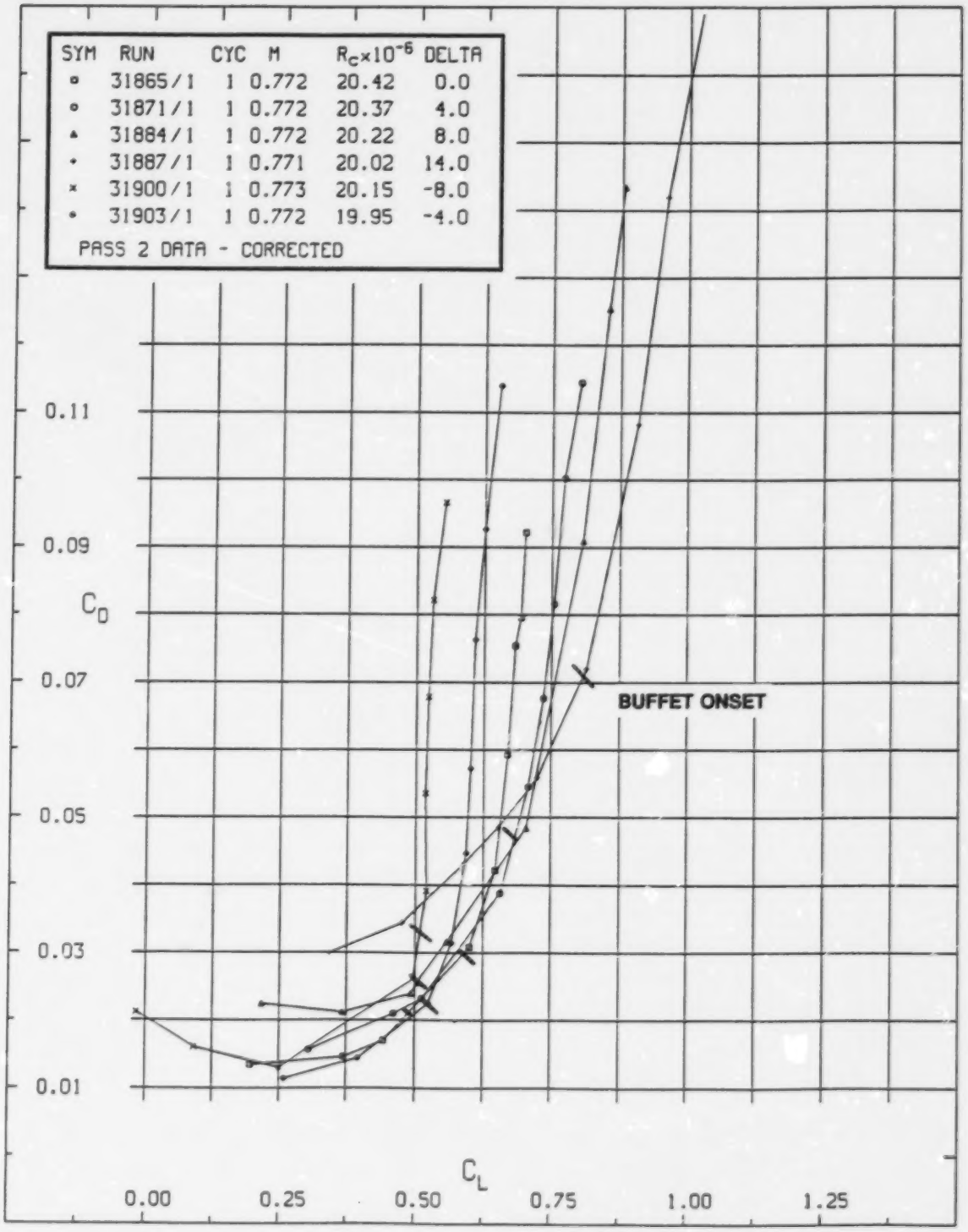

FIG. 49: DRAG VERSUS LIFT AT M ABOUT 0.772 FOR VARIOUS FLAP ANGLES

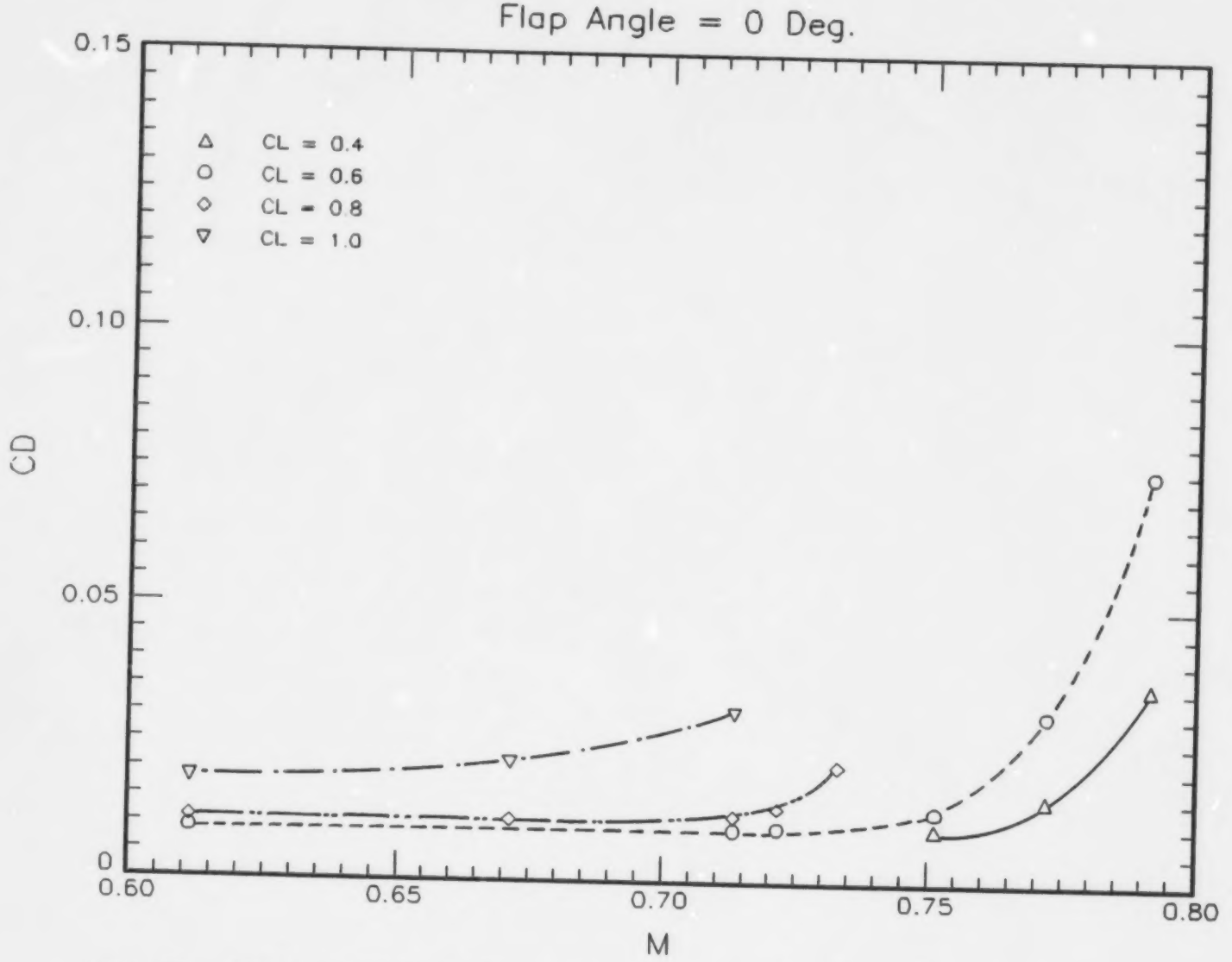

FIG. 50: DRAG VERSUS MACH NUMBER AT VARIOUS LIFT COEFFICIENTS FOR FLAP ANGLE $\delta = 0°$

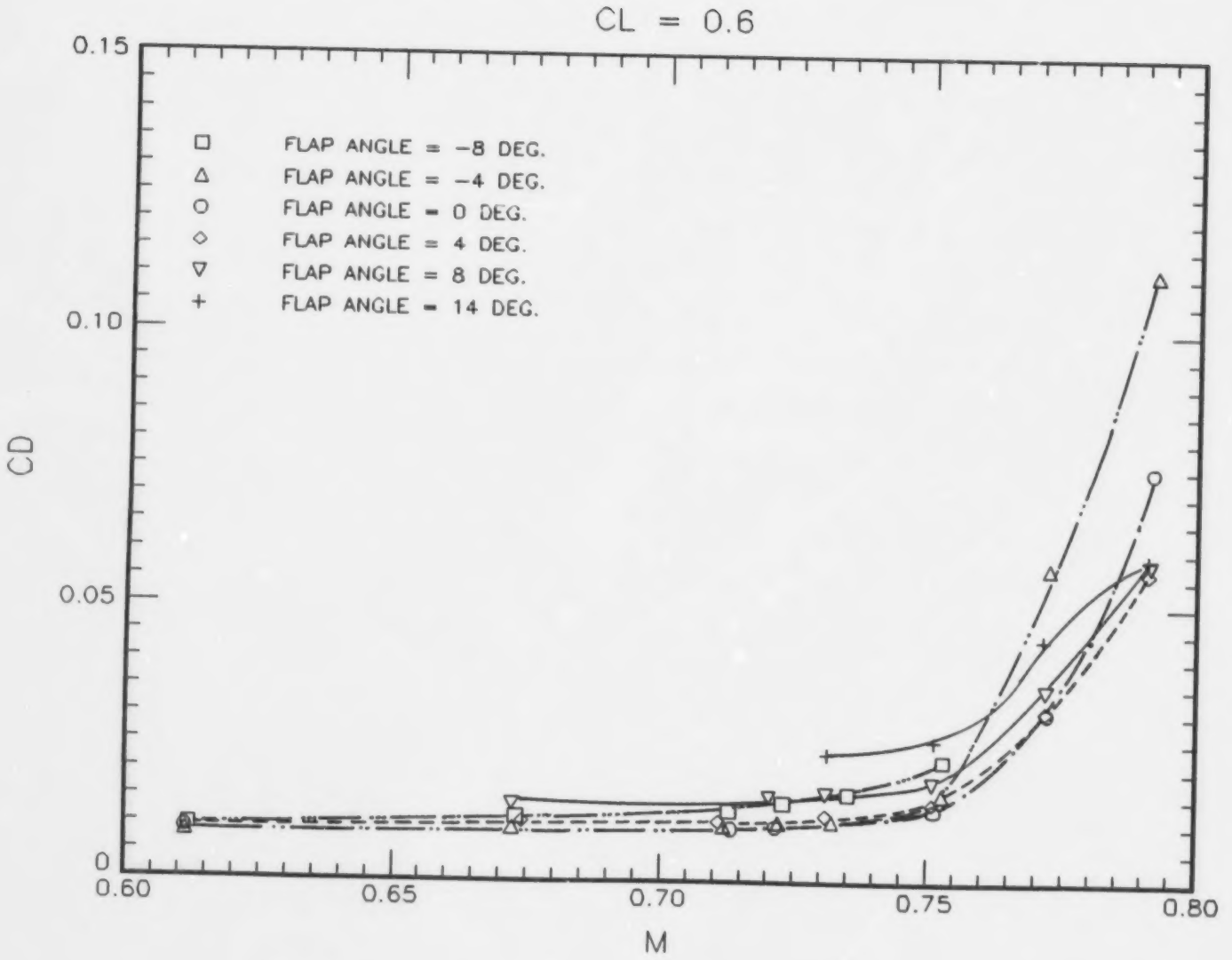

FIG. 51: DRAG VERSUS MACH NUMBER AT $C_L = 0.6$ FOR VARIOUS FLAP ANGLES

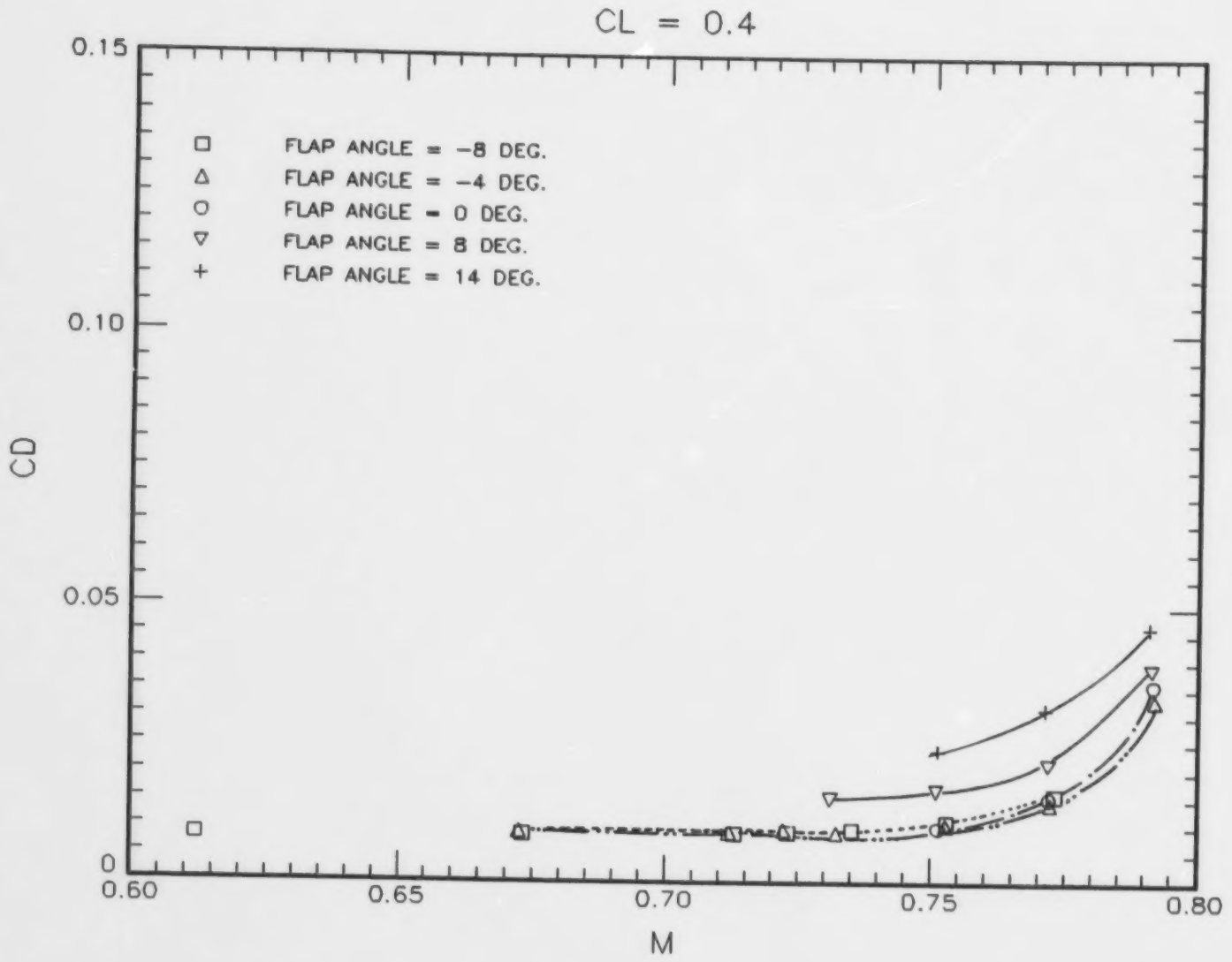

FIG. 52: DRAG VERSUS MACH NUMBER AT C_L = 0.4 FOR VARIOUS FLAP ANGLES

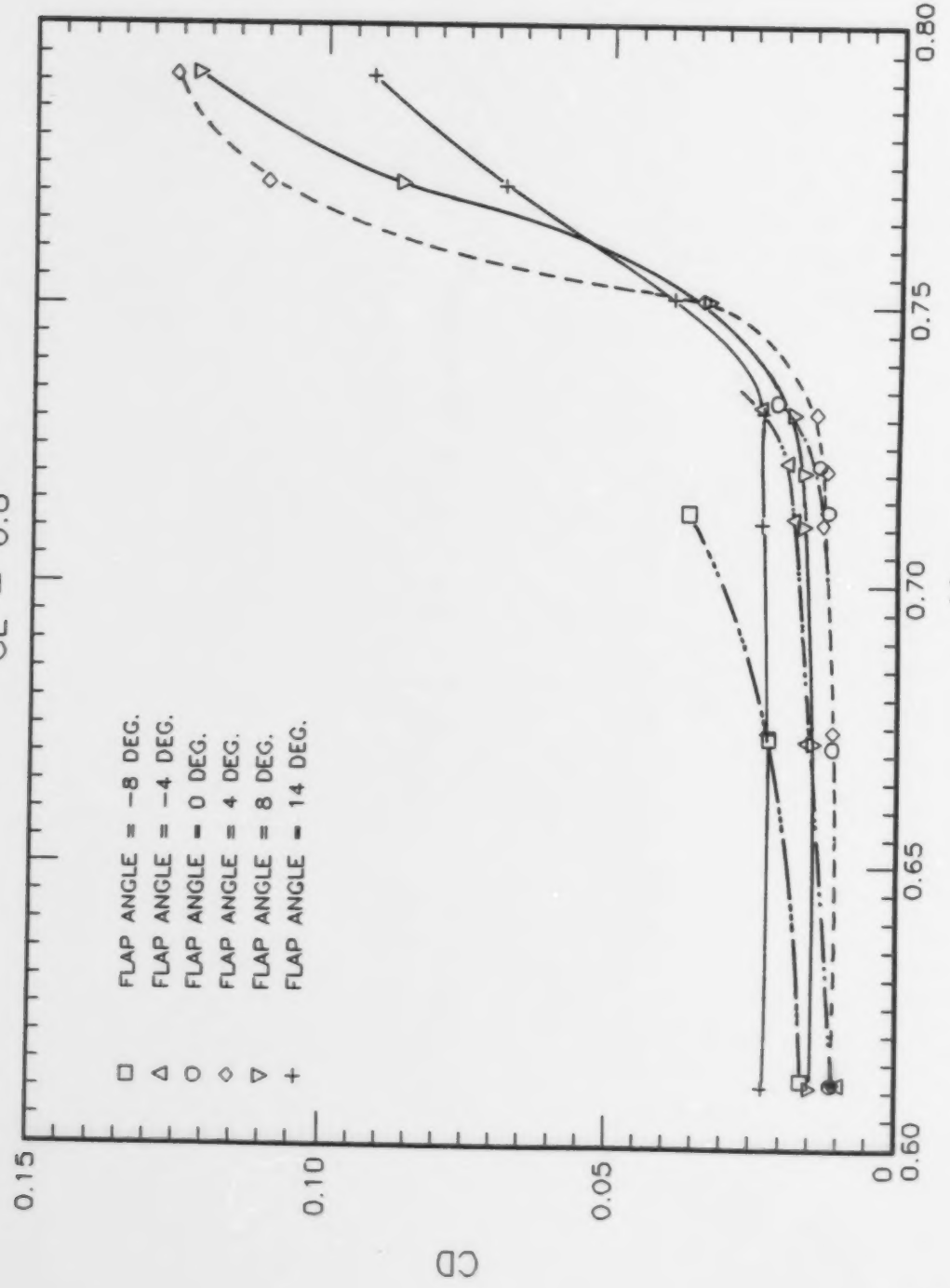

FIG. 53: DRAG VERSUS MACH NUMBER AT C_L = 0.8 FOR VARIOUS FLAP ANGLES

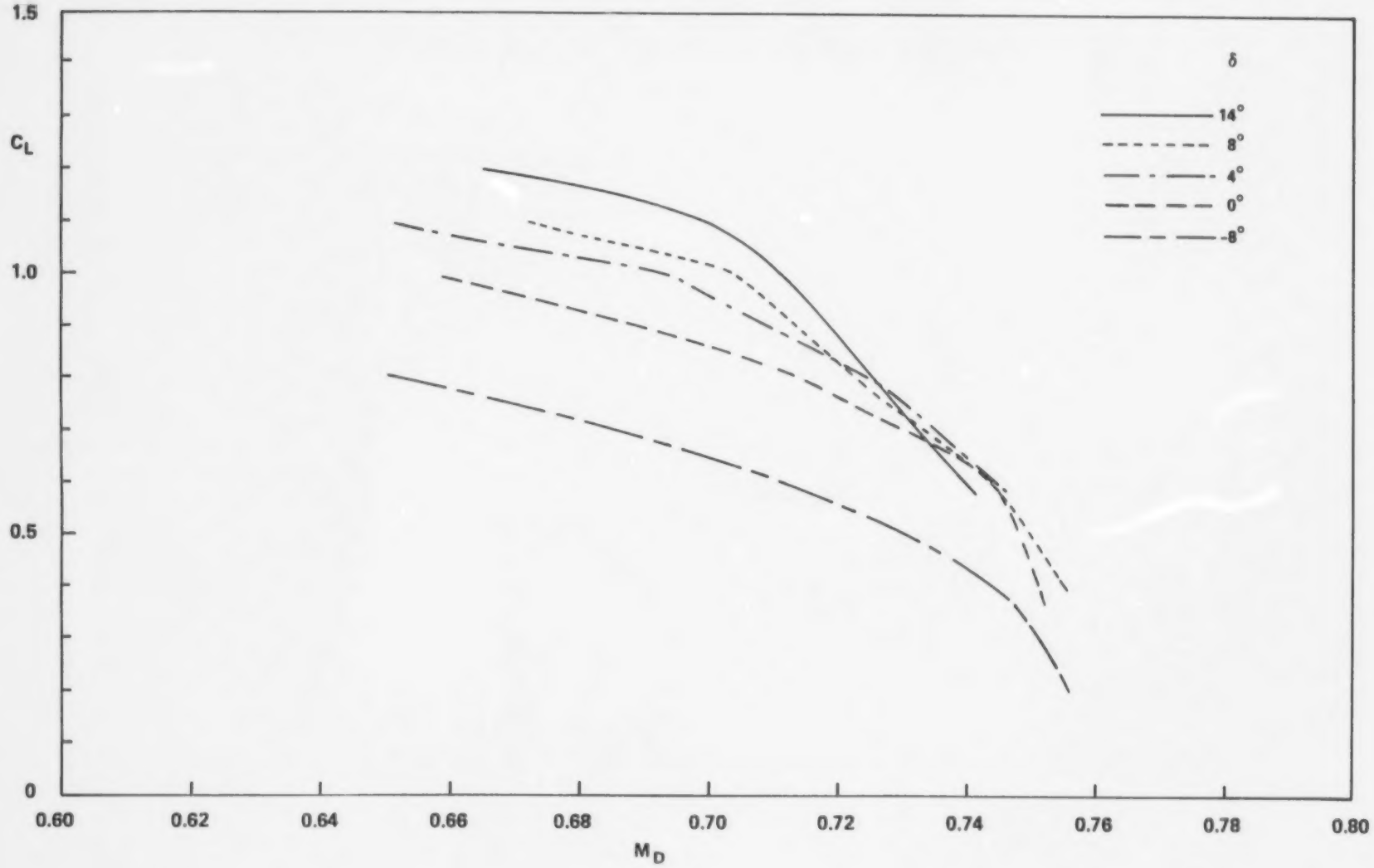

FIG. 54: LIFT VERSUS DRAG RISE MACH NUMBER FOR VARIOUS FLAP ANGLES

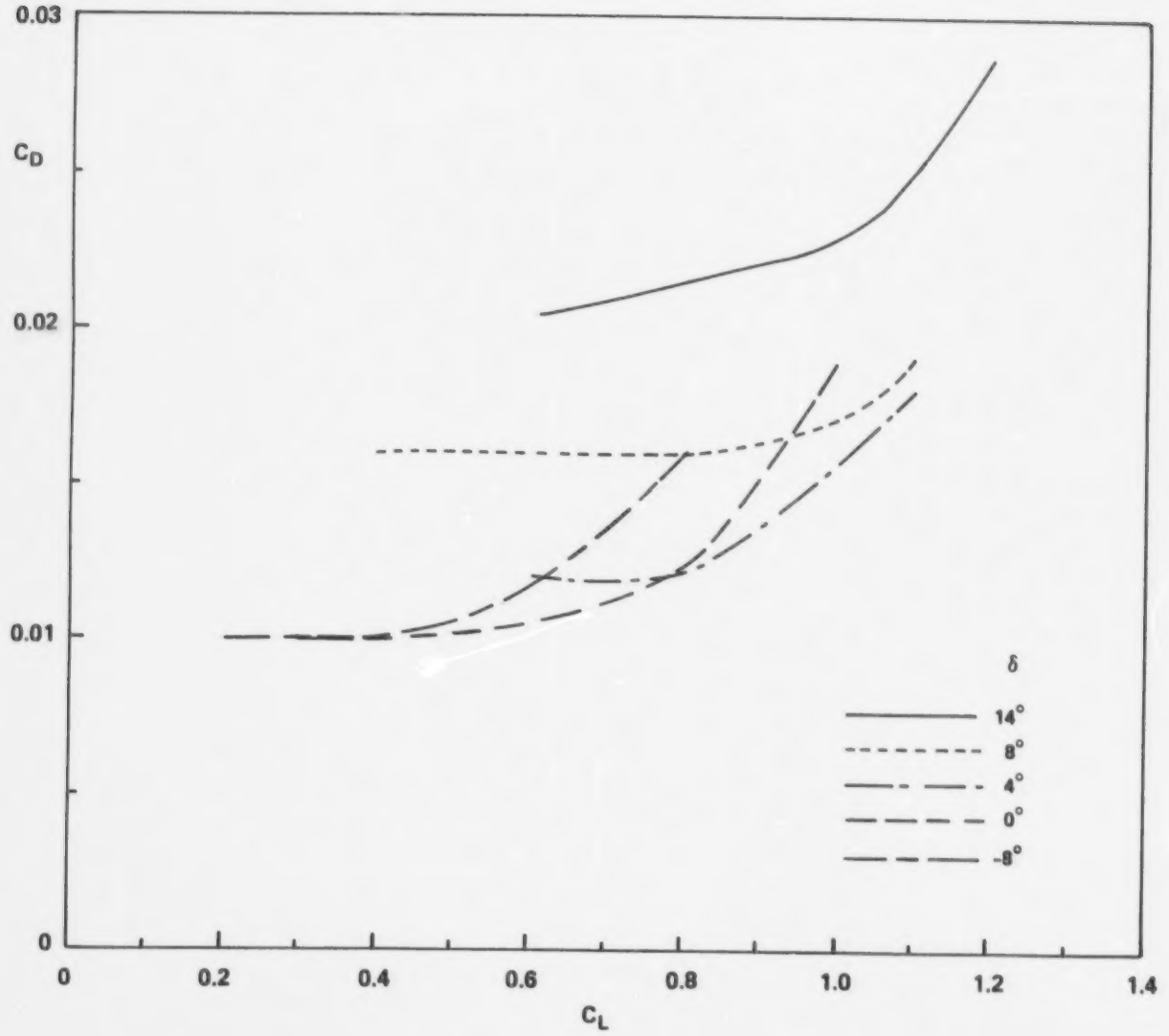

FIG. 55: DRAG VERSUS LIFT AT DRAG RISE MACH NUMBER FOR VARIOUS FLAP ANGLES

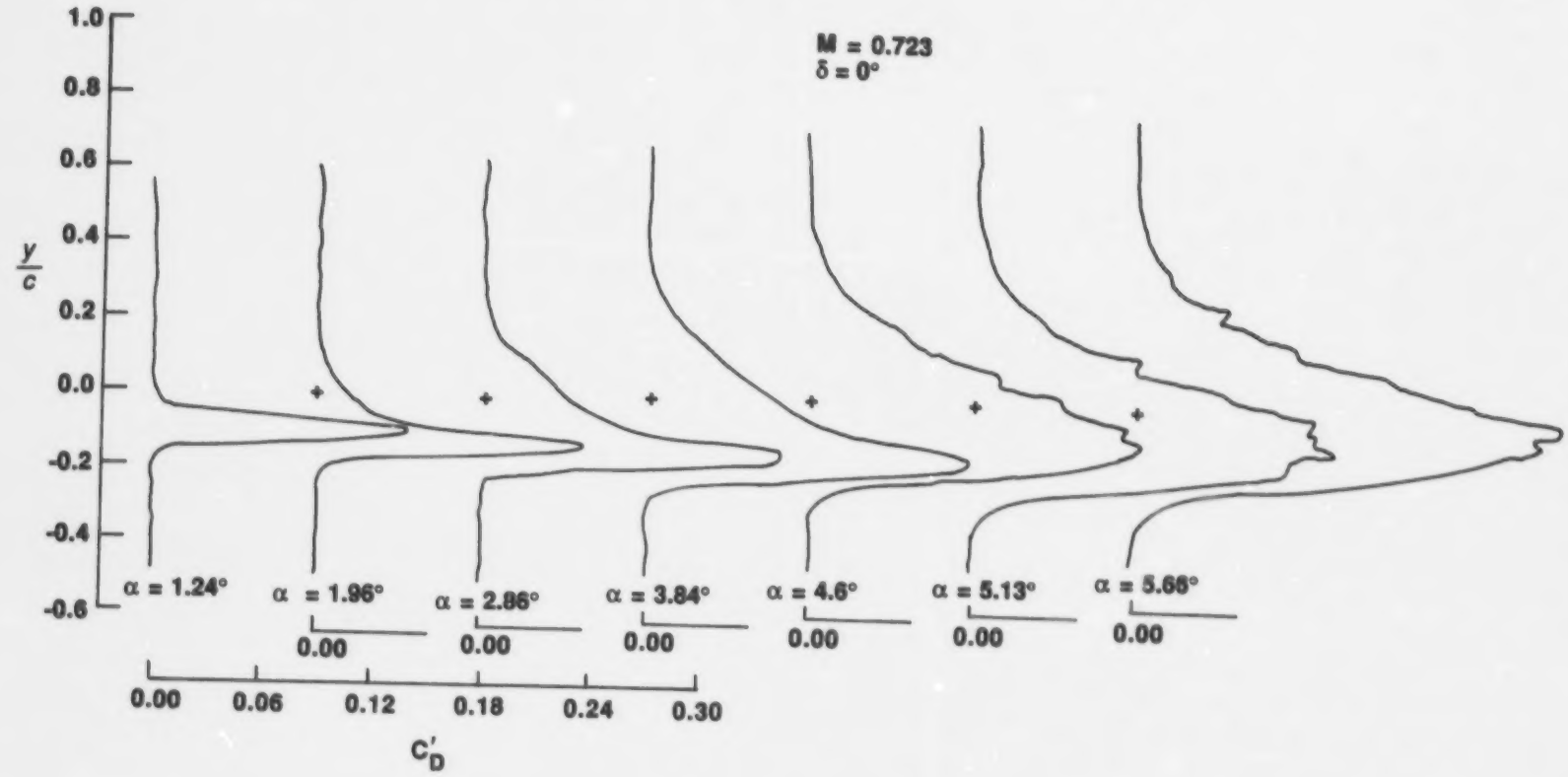

FIG. 56: WAKE PROFILES AT M = 0.723 and δ = 0° FOR VARIOUS ANGLES OF INCIDENCE

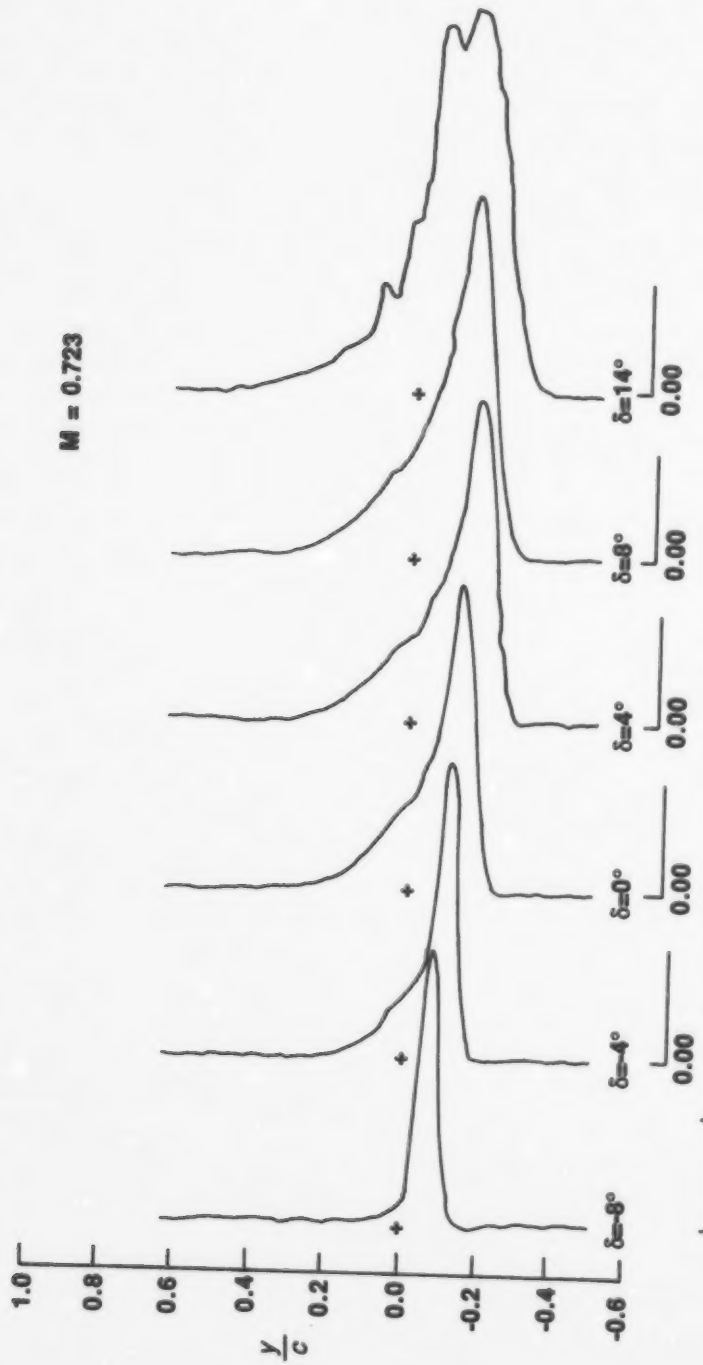

FIG. 57: WAKE PROFILES AT M = 0.723 AND α ABOUT 2.75°
FOR VARIOUS FLAP ANGLES

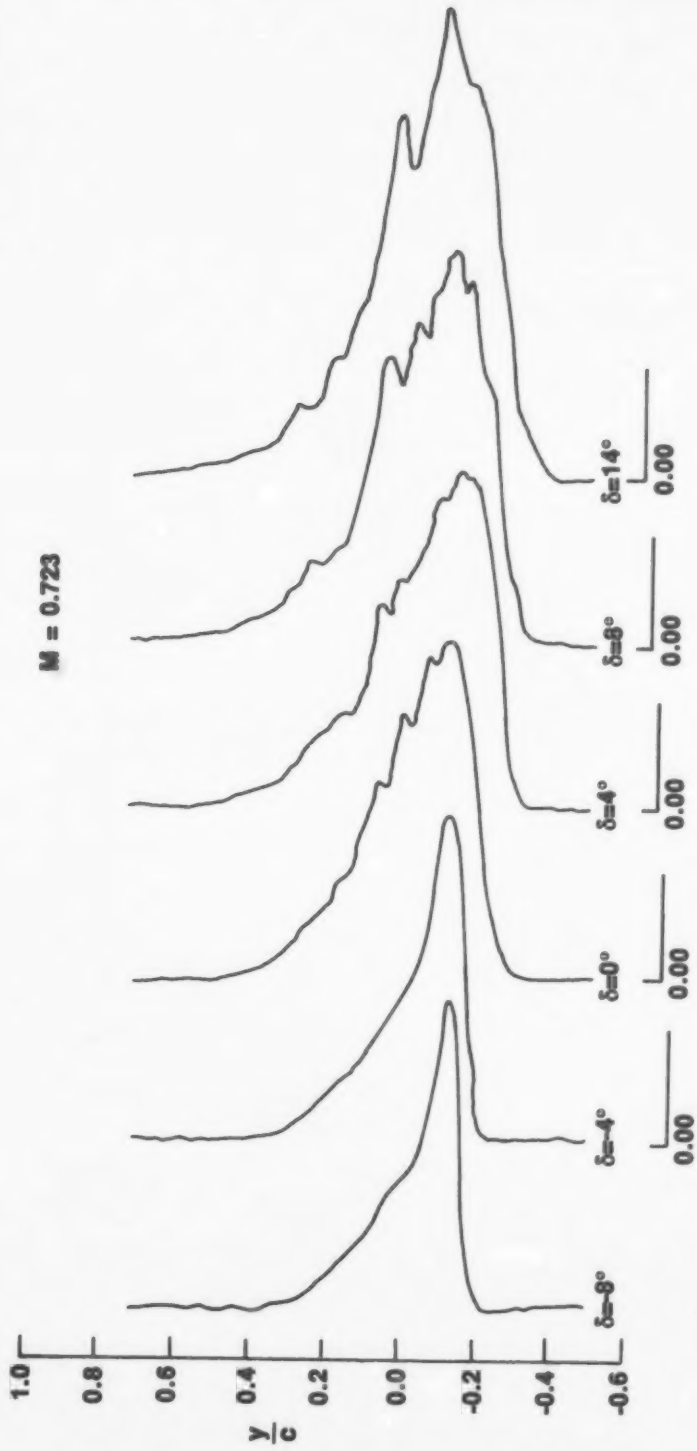

FIG. 58: WAKE PROFILES AT M = 0.723 AND α ABOUT 4.5° FOR VARIOUS FLAP ANGLES

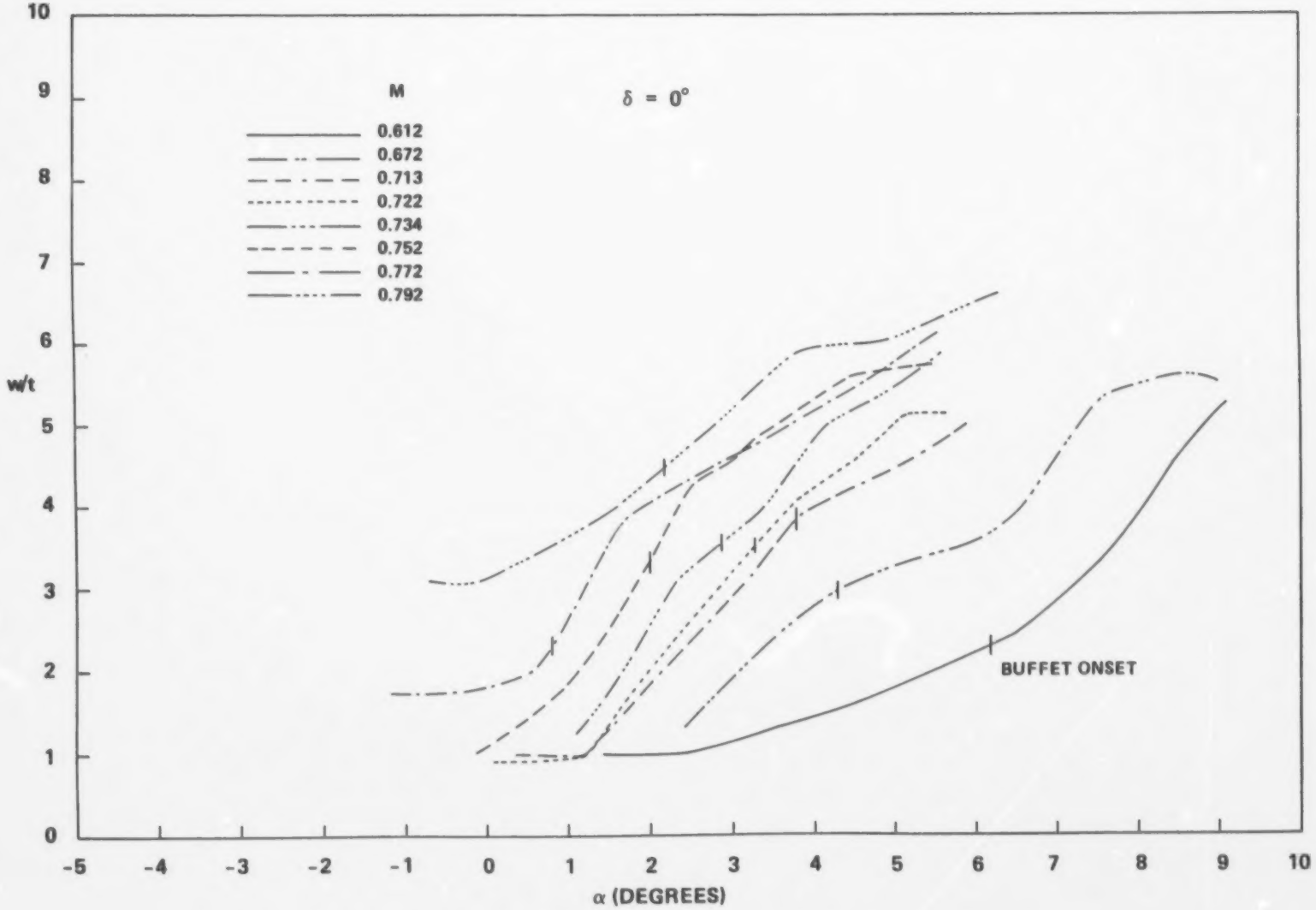

FIG. 59: WAKE WIDTH VERSUS ANGLE OF INCIDENCE FOR VARIOUS MACH NUMBERS AT δ = 0°

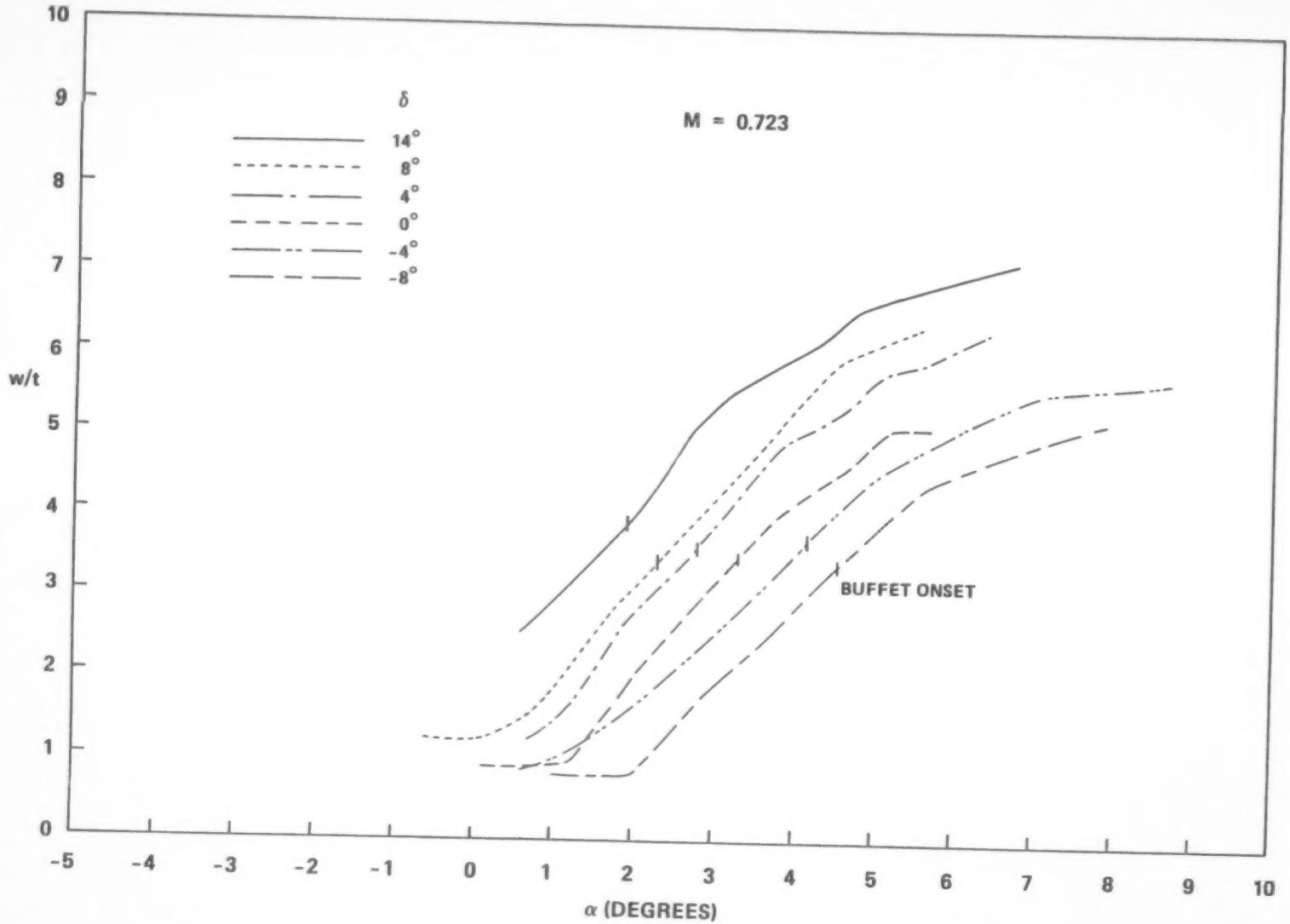

FIG. 60: WAKE WIDTH VERSUS ANGLE OF INCIDENCE AT M = 0.723 FOR VARIOUS FLAP ANGLES

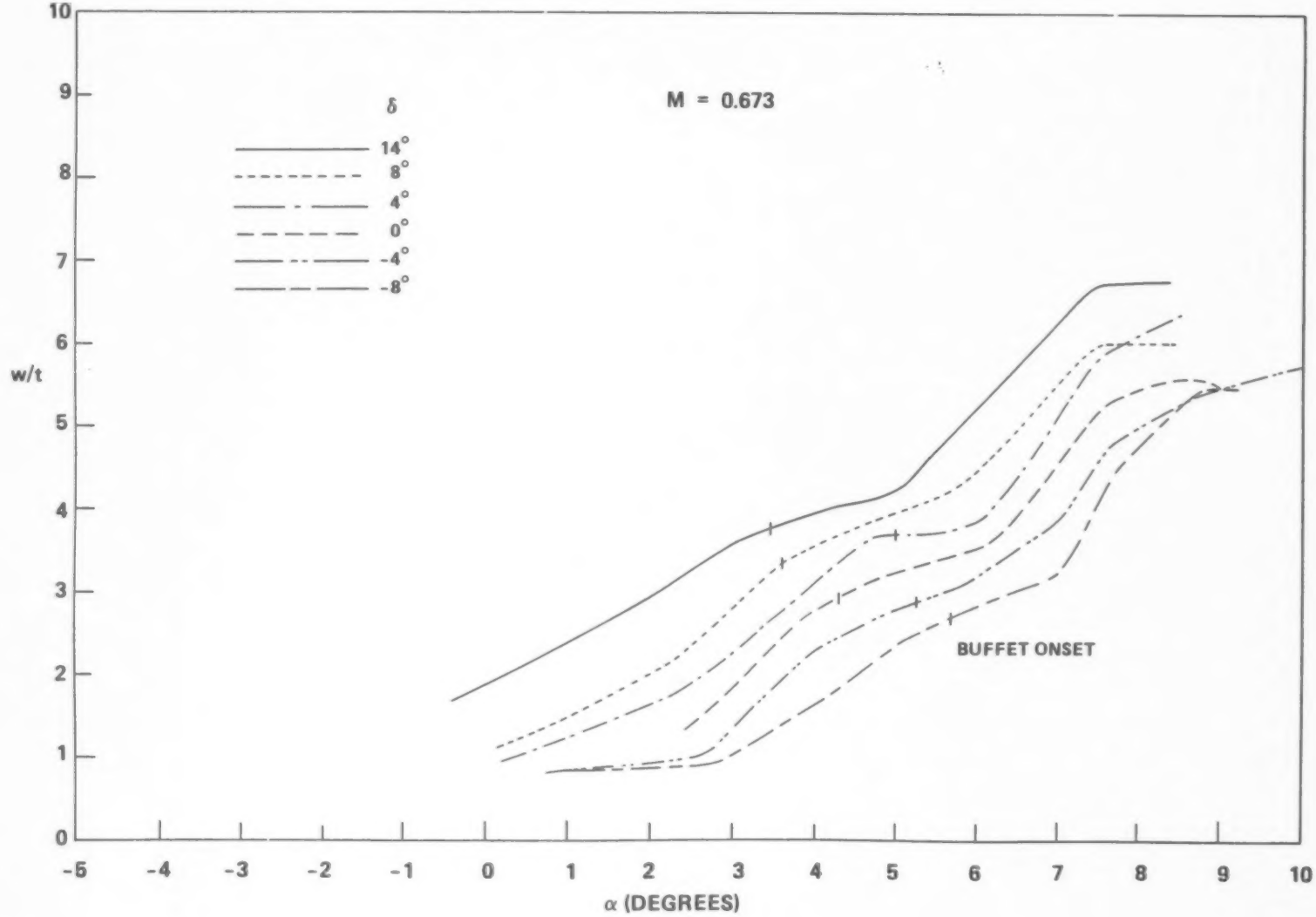

FIG. 61: WAKE WIDTH VERSUS ANGLE OF INCIDENCE AT M = 0.673 FOR VARIOUS FLAP ANGLES

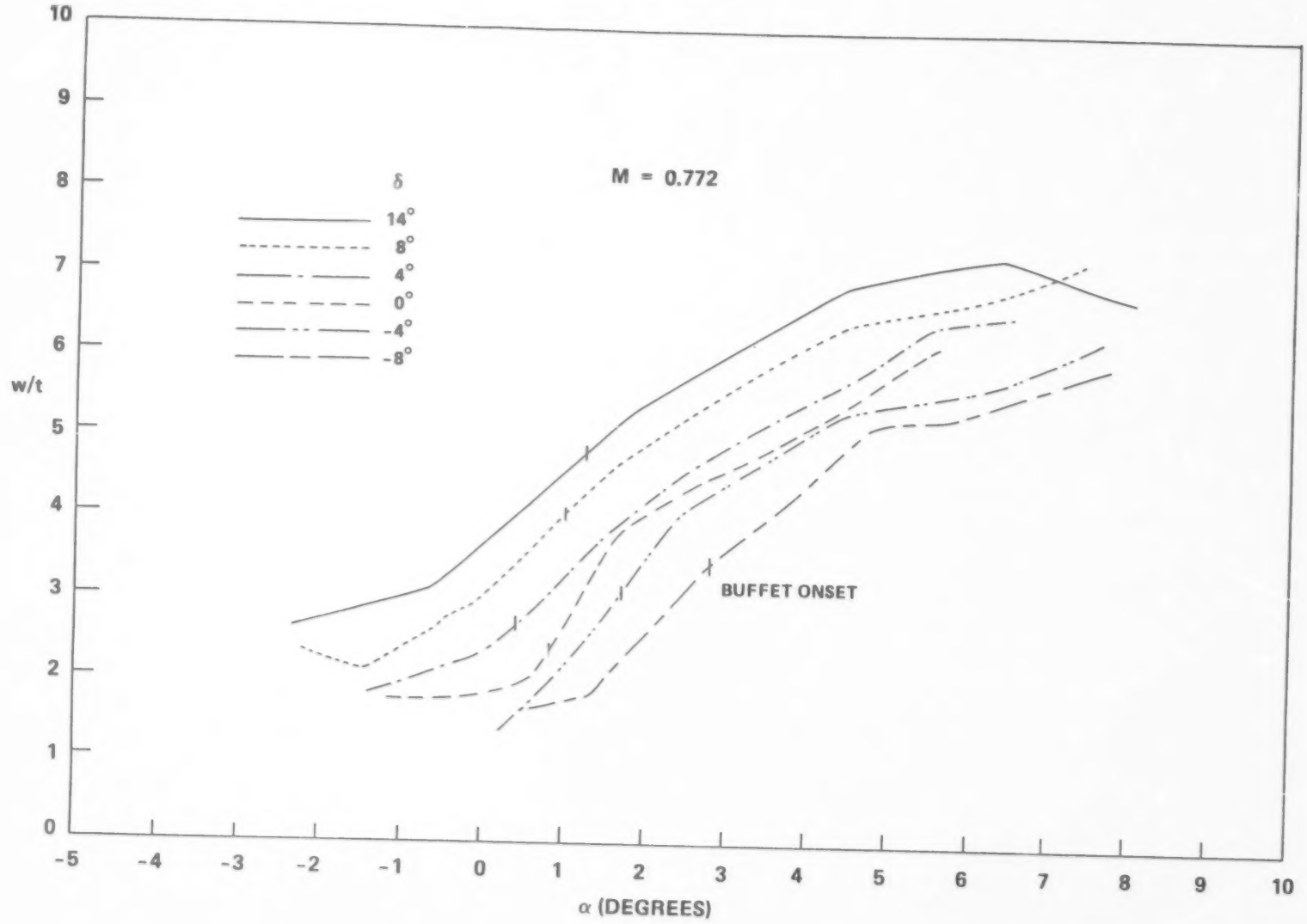

FIG. 62: WAKE WIDTH VERSUS ANGLE OF INCIDENCE AT M = 0.772 FOR VARIOUS FLAP ANGLES

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An Experimental Study of Transonic Buffet of a Supercritical Airfoil with Trailing Edge Flap

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DESCRIPTORS (KEY WORDS)/MOTS-CLÉS (14)

1. Airfoils — Supercritical
2. Airfoils — Trailing edge flaps
3. Transonic wind tunnels — Testing

SUMMARY/SOMMAIRE (15)

A supercritical airfoil with a trailing edge flap has been the subject of aerodynamic investigation in the National Aeronautical Establishment's High Reynolds Number 2-D Test Facility. The effects of flap deflection on buffet intensities and delay of buffet onset at transonic speeds were studied. Buffet boundaries for various flap angles were determined from the divergence of the fluctuating balance normal force measurements (C_N'). The onset of buffet was obtained from plots of C_N' versus C_L at values of C_L where the slope was 0.1. This value for the slope was arbitrarily chosen, but was found to give consistent results which agreed well with values computed from the criterion using the trailing edge pressure divergence for those cases where buffet onset is primarily due to trailing edge separation.

For given flow conditions the deflection of the trailing edge flap altered the circulation and hence the position of the shock wave and its strength. The variations of these two quantities with flap angles were determined from pressure measurements carried out on the airfoil surface. The test was performed quite deep inside the buffet régime and shock wave oscillations were investigated from spectral analyses of the balance output. Fluctuations in the shock motion of approximately 70 Hz were detected.

The drag of the airfoil was computed from the wake stagnation pressure deficit and the drag penalties for large flap angles were quite significant. Analysis of the wake profiles with flap settings was carried out to study the changes in wake characteristics.